Experimental Lecture #5
Reactor

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NBIA PhD School: Neutrinos Underground and in the Heavens
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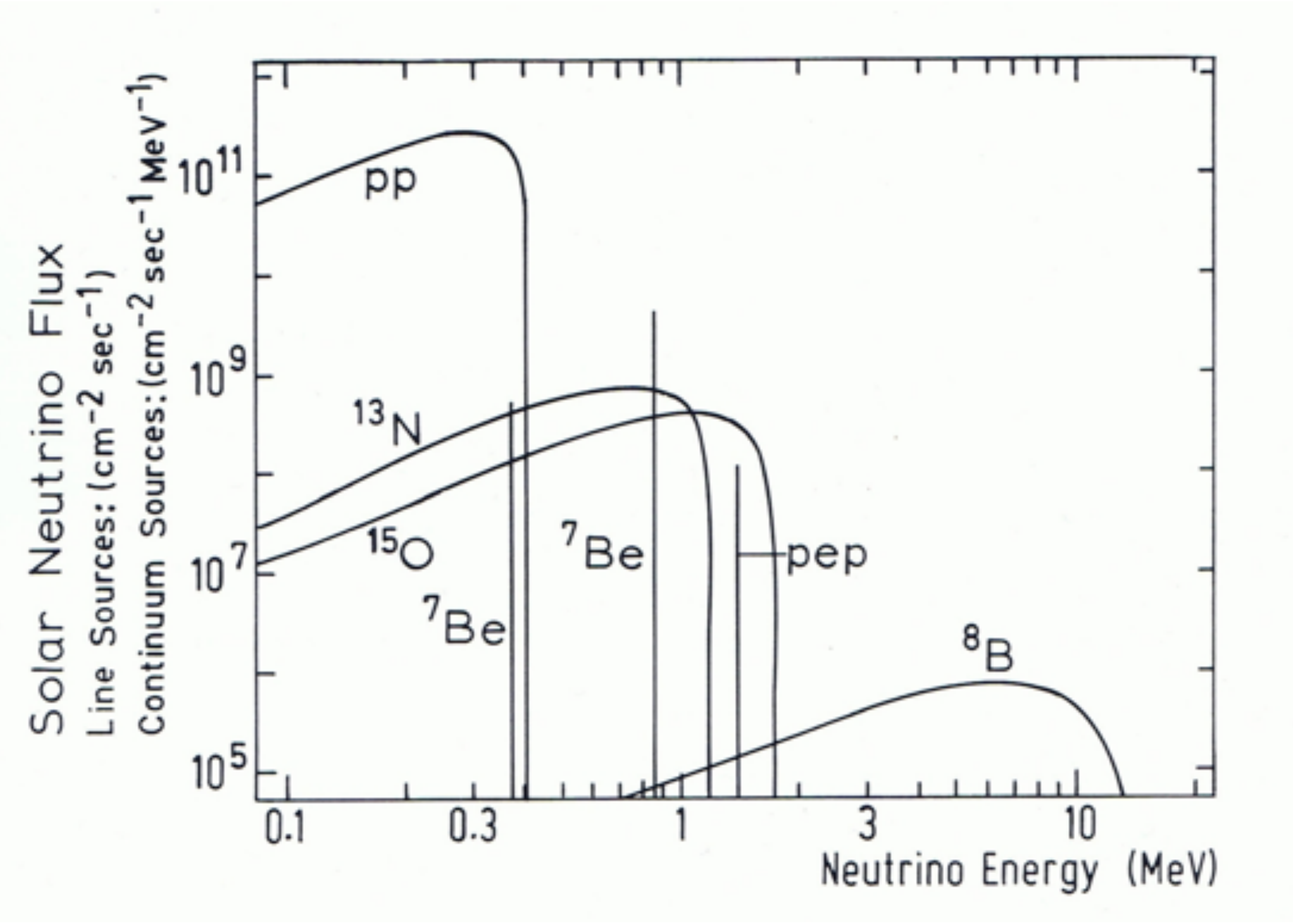
Niels Bohr Institutet

The Niels Bohr
International Academy

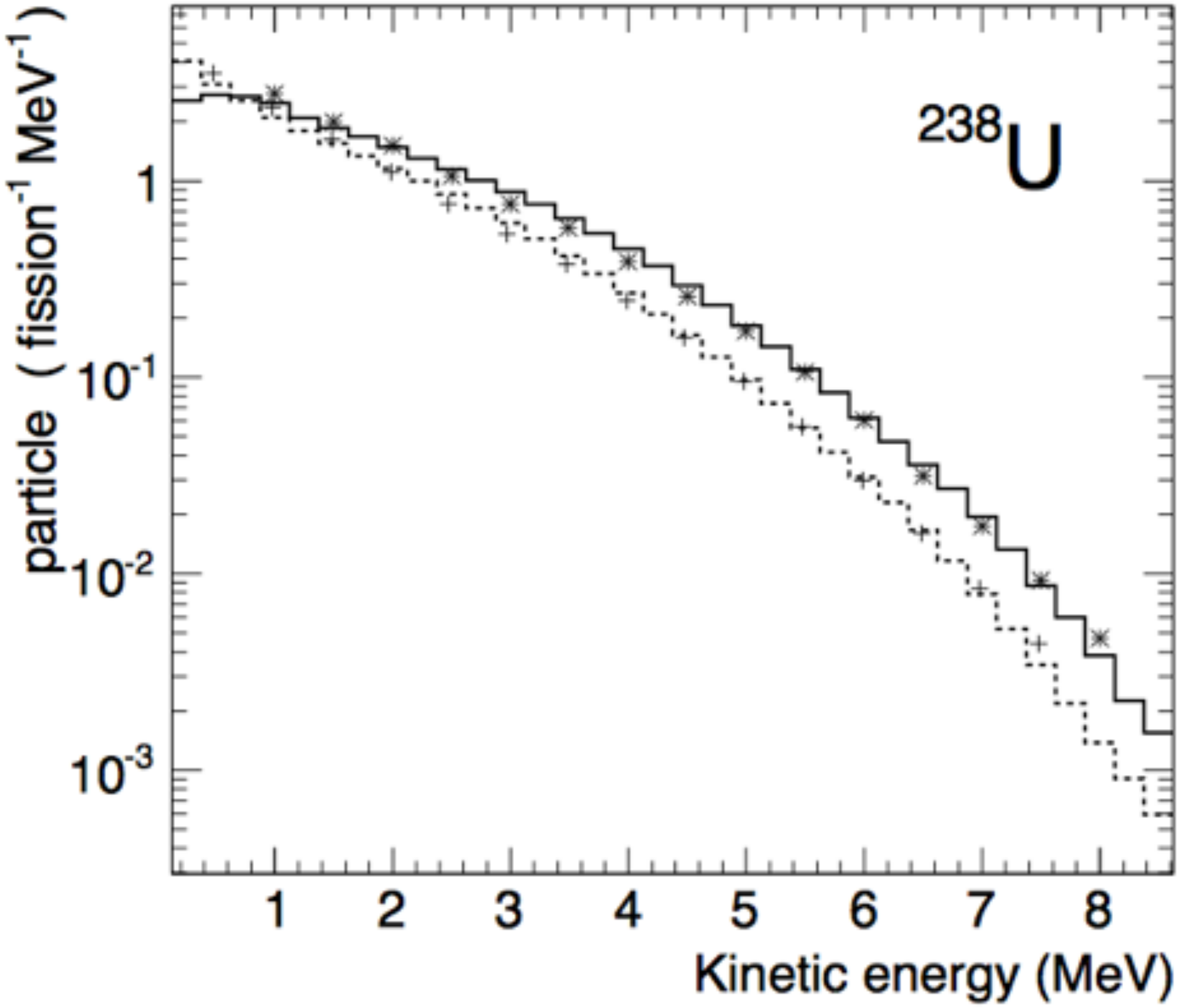
Discovery

KeV-MeV Energy - Solar/Reactor Neutrinos

Solar Neutrino Flux

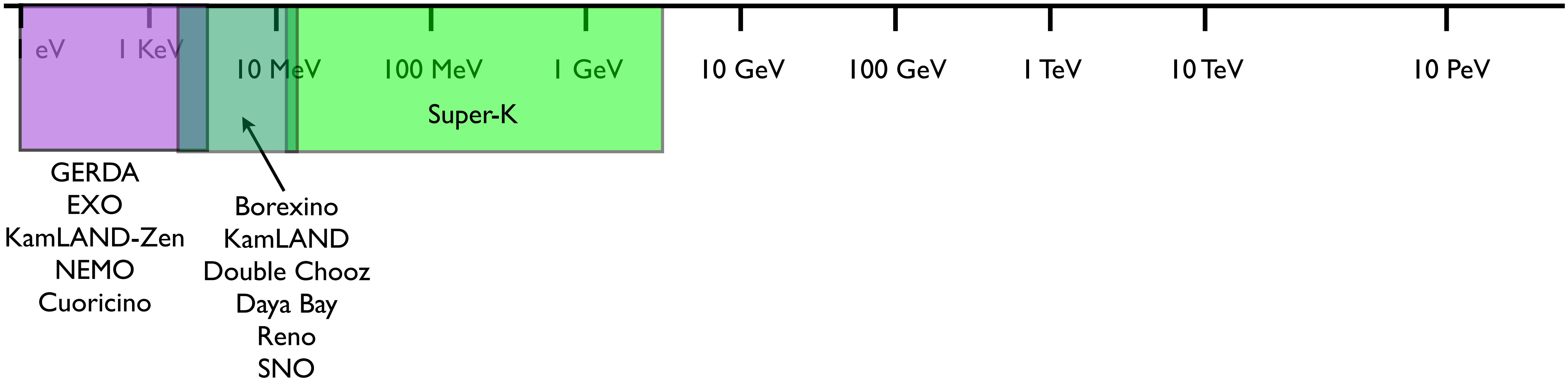


Reactor Neutrino Flux



Experimental Landscape

Accelerator based



GERDA
EXO
KamLAND-Zen
NEMO
Cuoricino

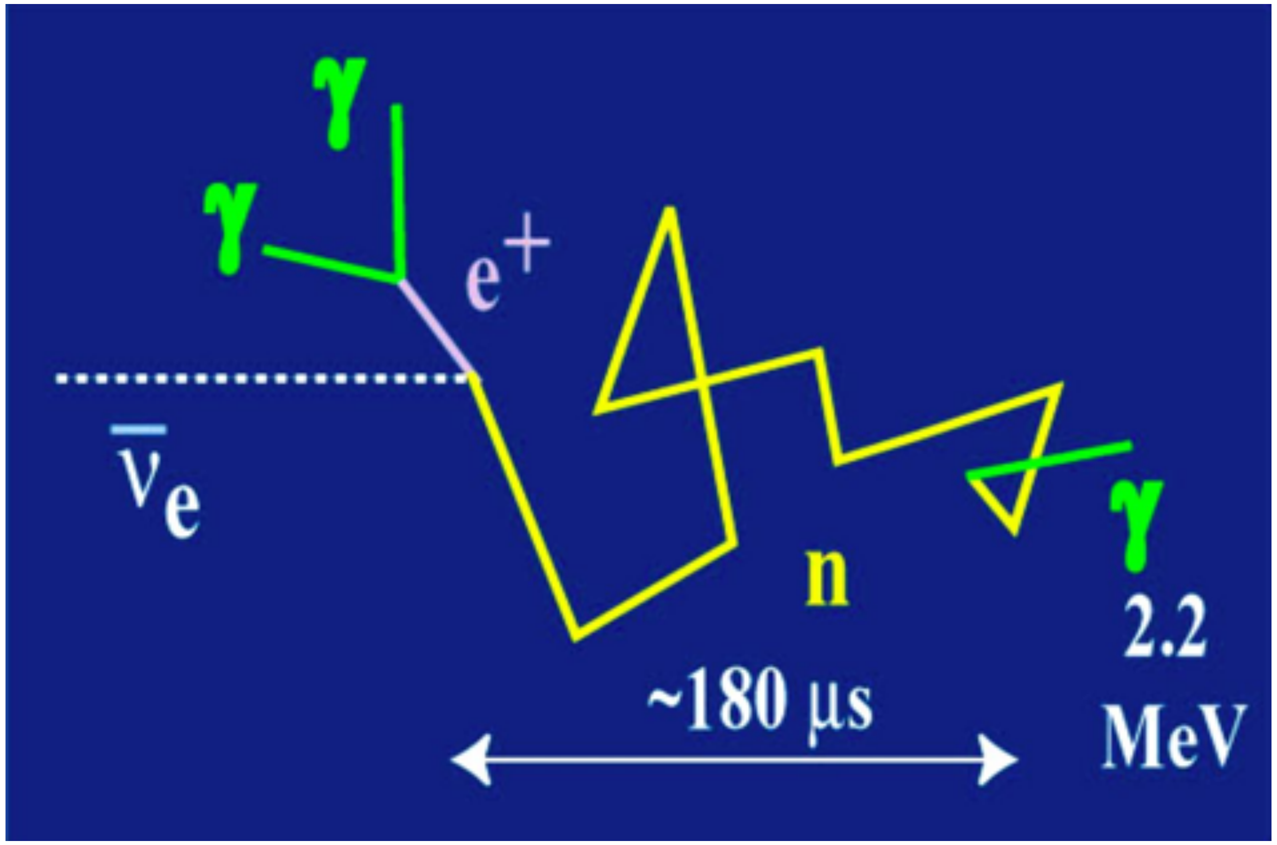
Borexino
KamLAND
Double Chooz
Daya Bay
Reno
SNO

Non-accelerator based

*Boxes provide sense of scale for physics sensitive regions

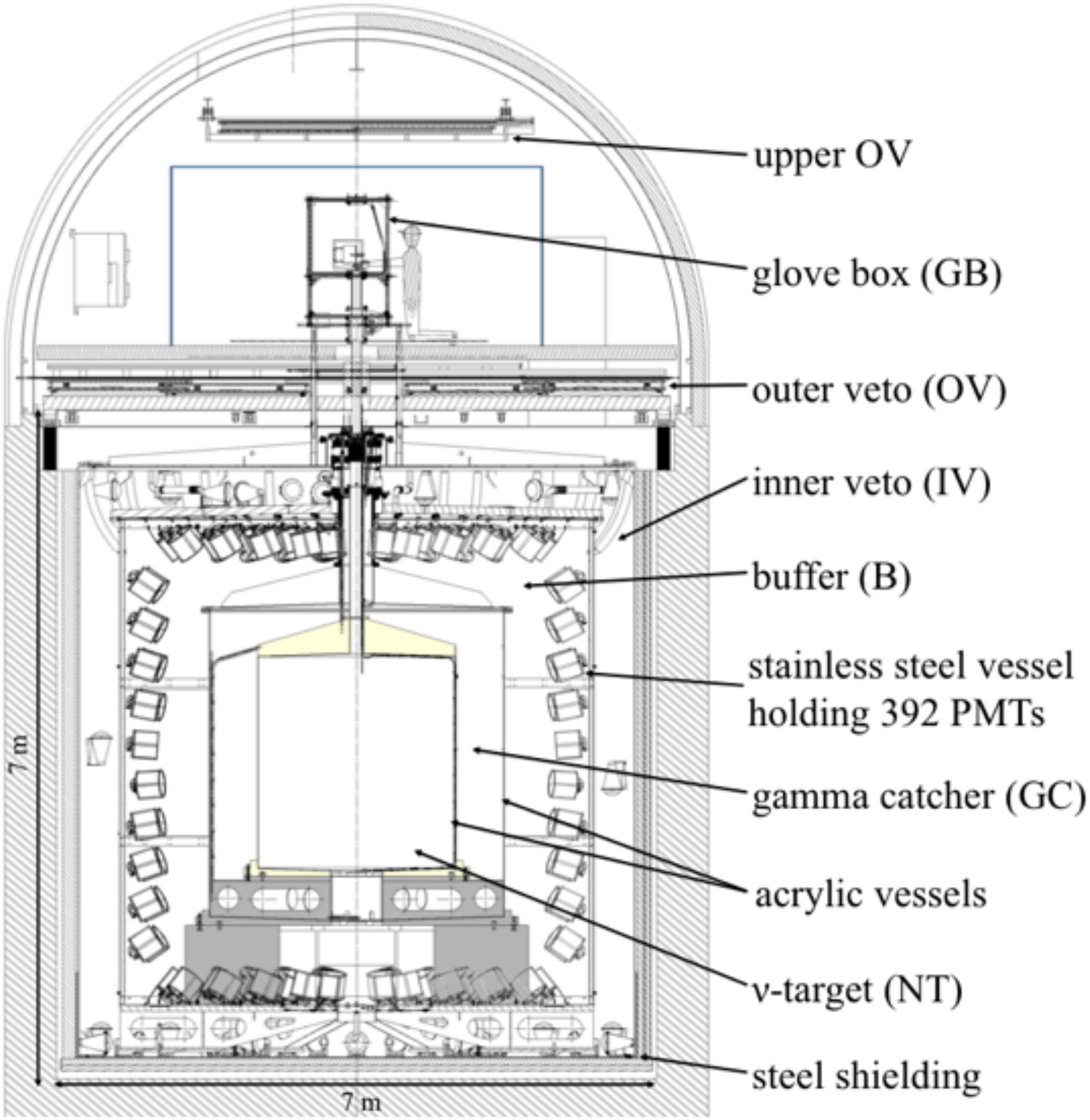
Liquid Scintillator

- Mainly inverse beta-decay for anti-neutrino detection
  - Positron annihilates with atomic electron
  - Neutron is absorbed by a doping agent at a characteristic time afterwards
- Prompt light from positron annihilation followed by delayed light



Detectors

- Detector material must be low, low, low radioactivity
- 'Chimney' for lowering radioactive calibration sources
- Layered
    - Outer veto layer - catch nearby muons
    - Inner veto - catch penetrating muons
    - Gamma catcher - absorb photons from nearby radioactive decay from PMTs, steel, etc.
    - Fiducial volume separated from innermost veto volume by transparent barrier

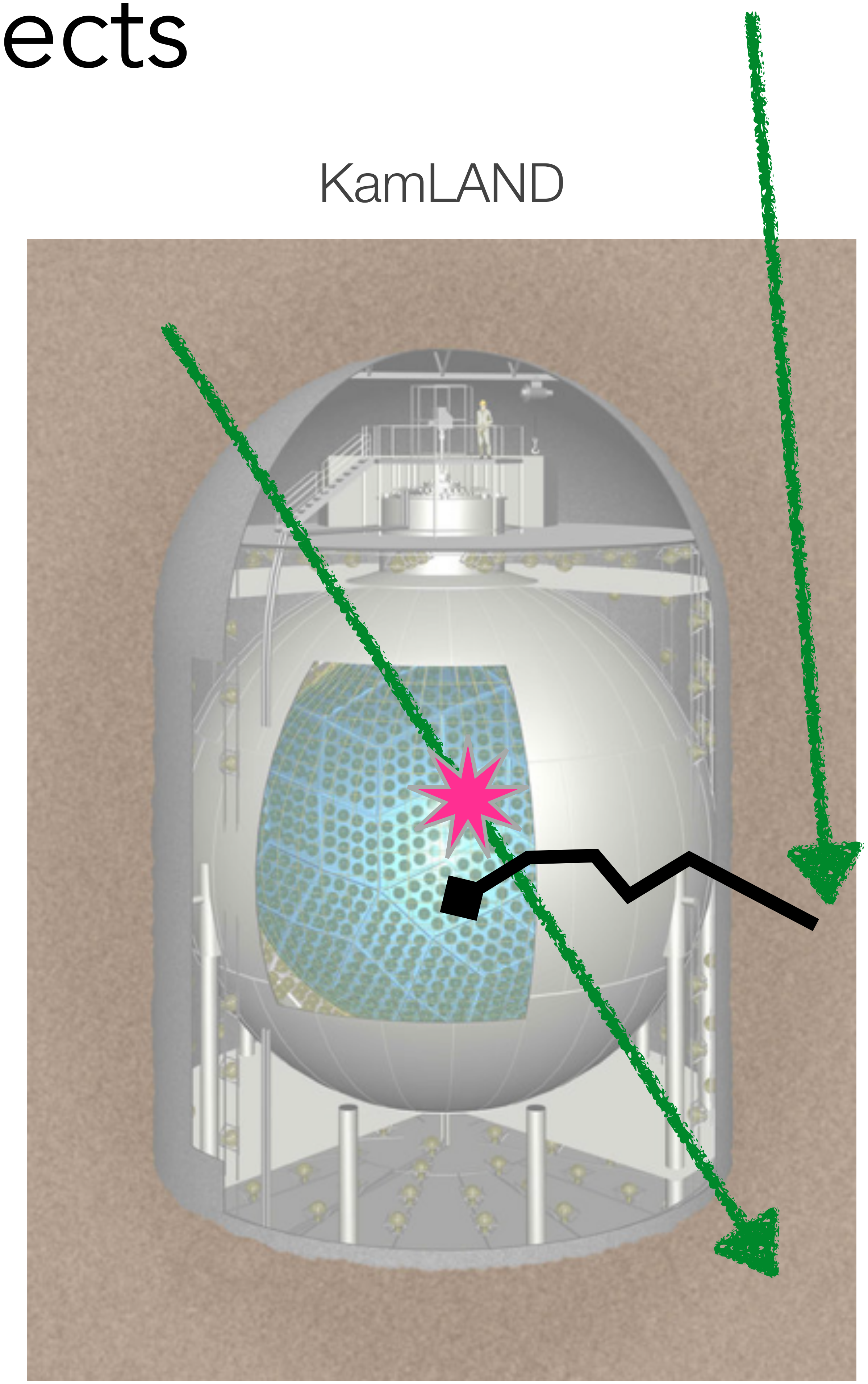


Daya Bay

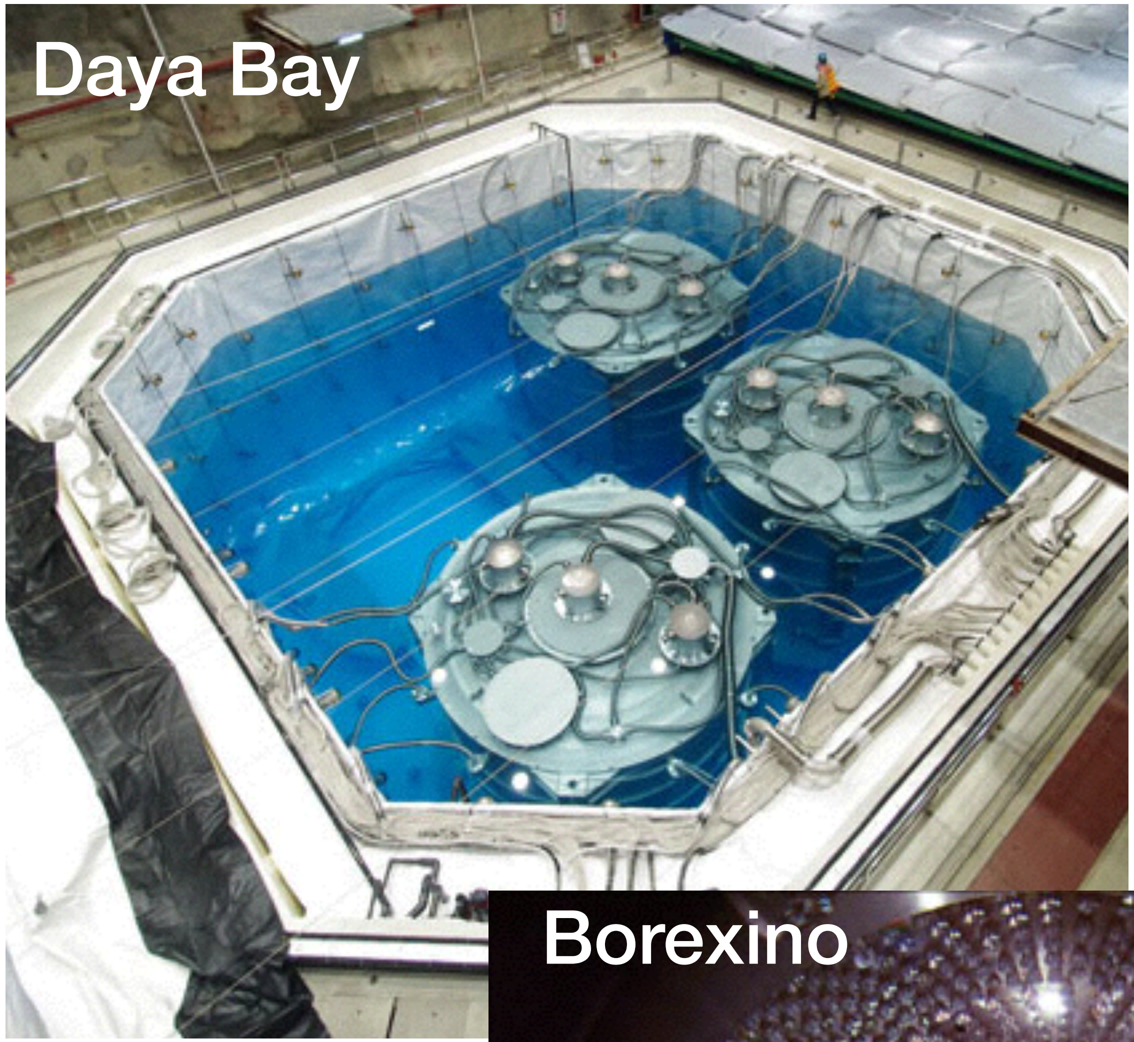
Secondary Muon Effects

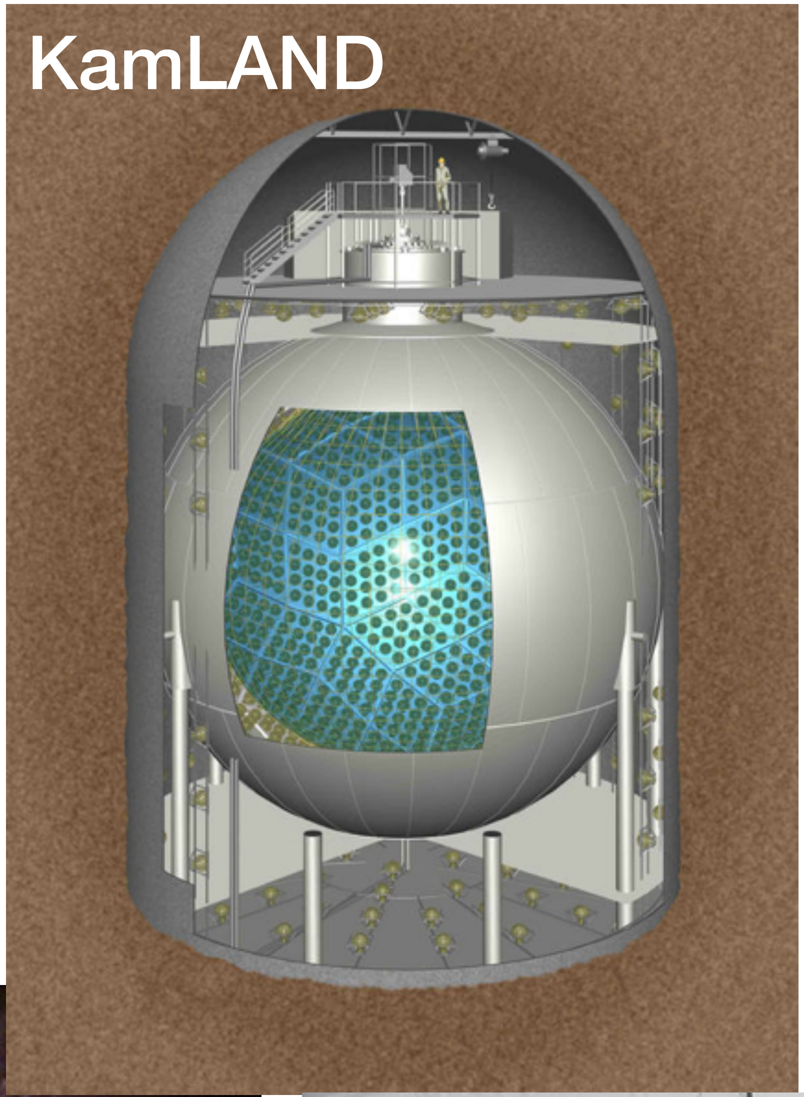
- Muons can cause radioactive background
  - **Cosmogenic activated radiation**, i.e. cosmic ray muon creates isotope within the detector which decays long after the muon is gone
  - Muons can dislodge **neutrons** which wander undetected into the detector whereupon they are absorbed or collide

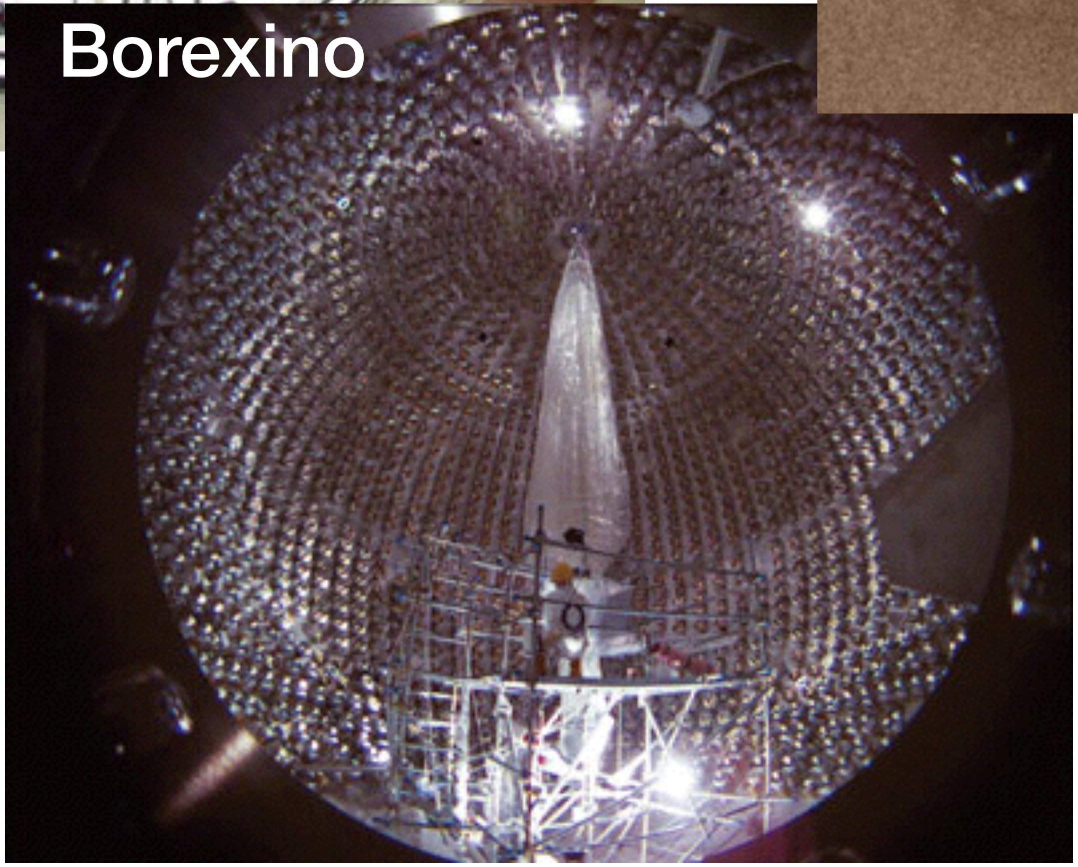
KamLAND

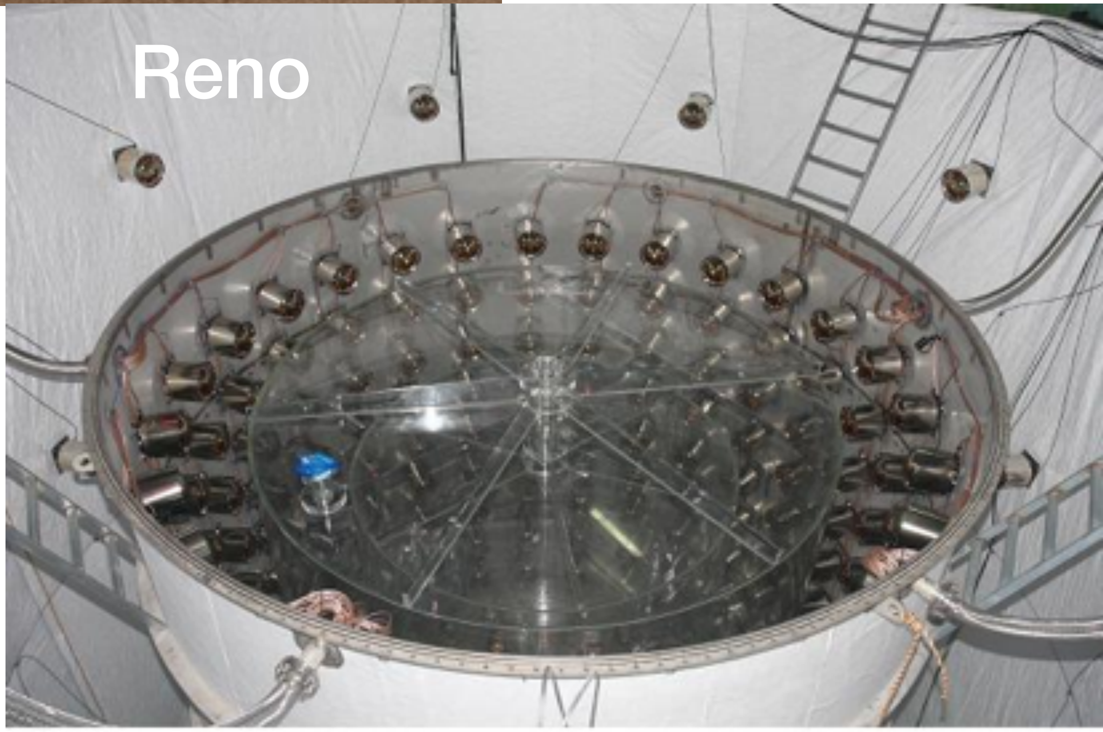


Variations







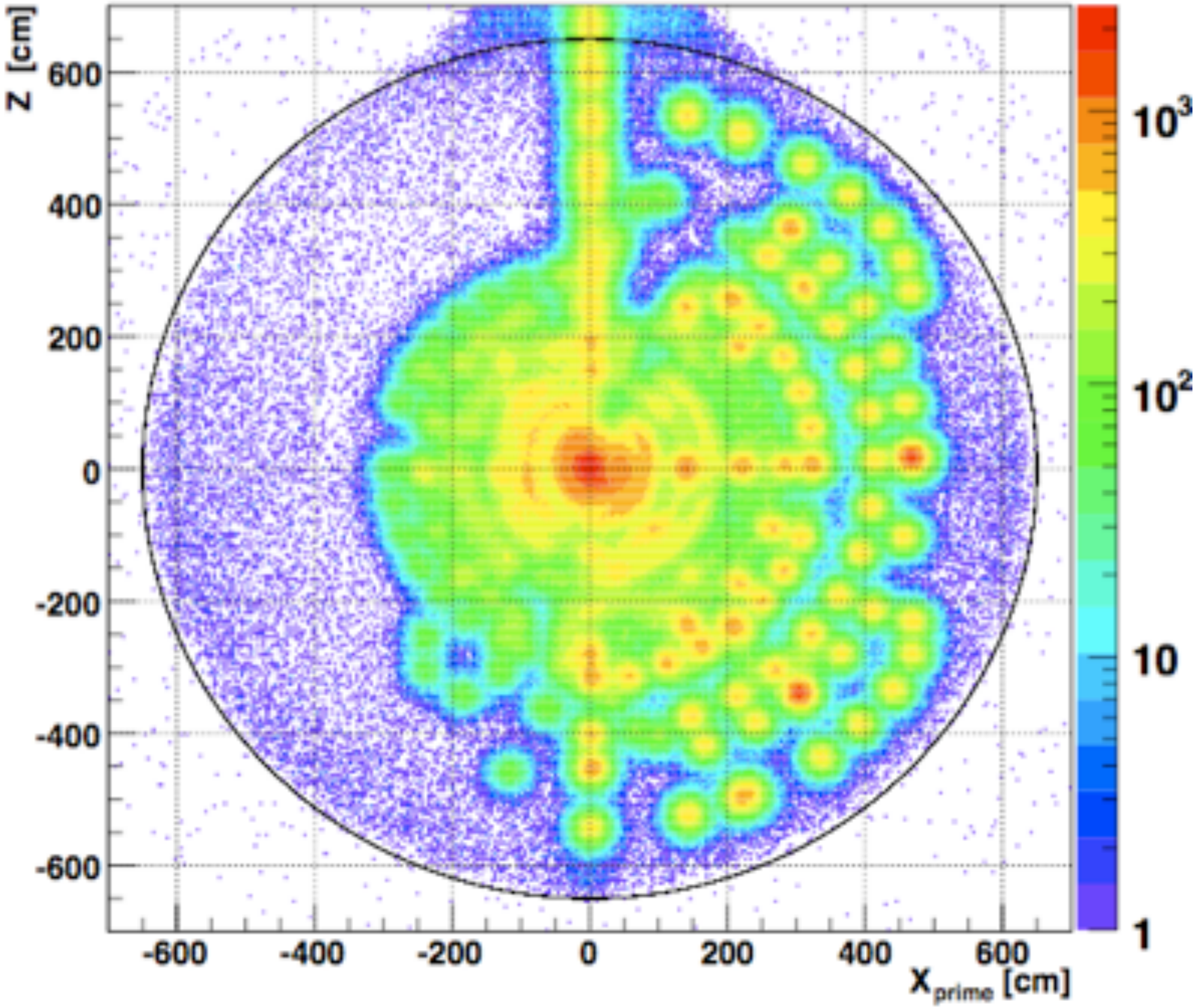


Calibration (KamLAND)

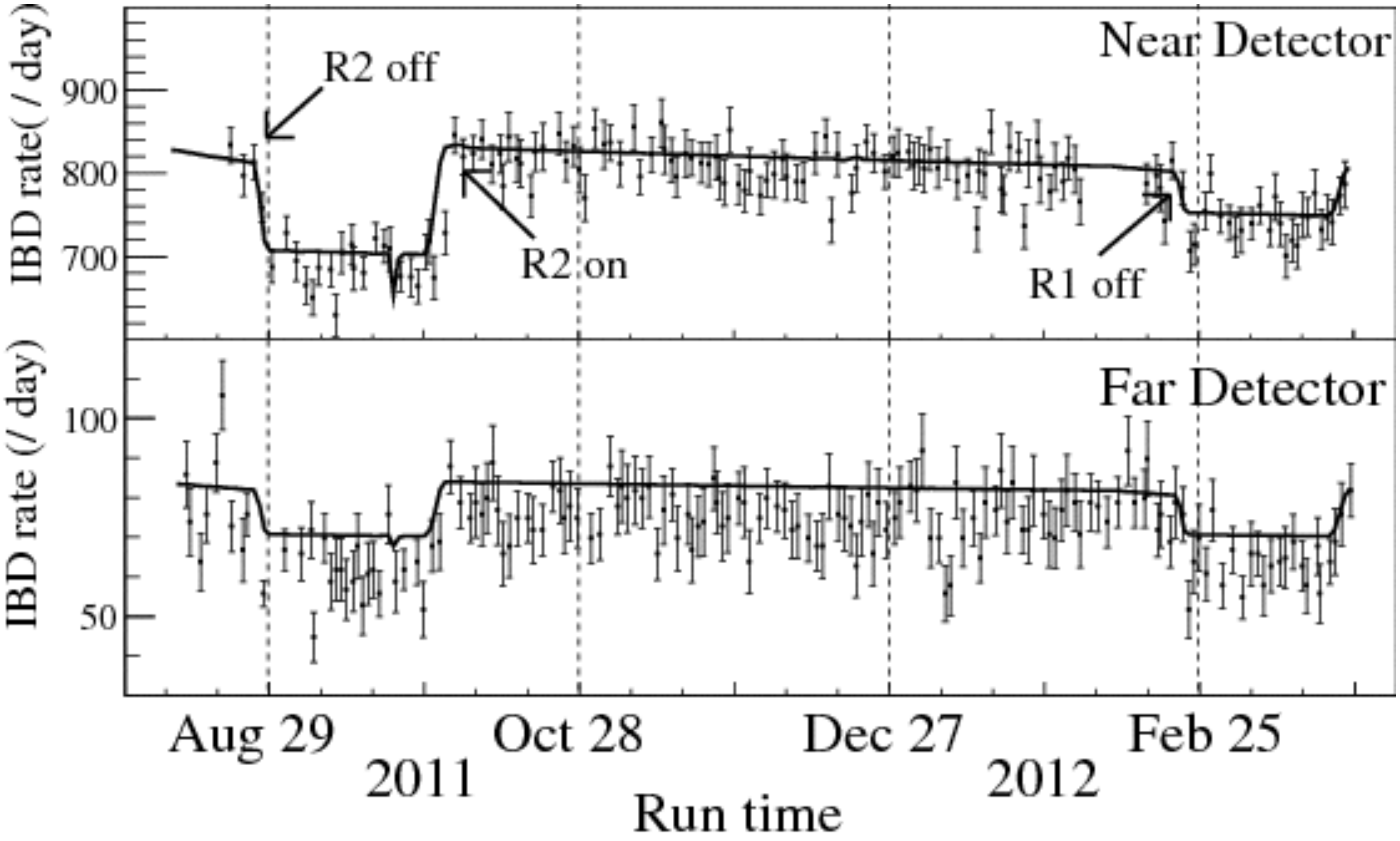
- Event vertex calibration and light response as a function of position

- Monitors any detector non-uniformities

- Slightly dangerous because there is a passage from an outside region into the immaculately clean detector

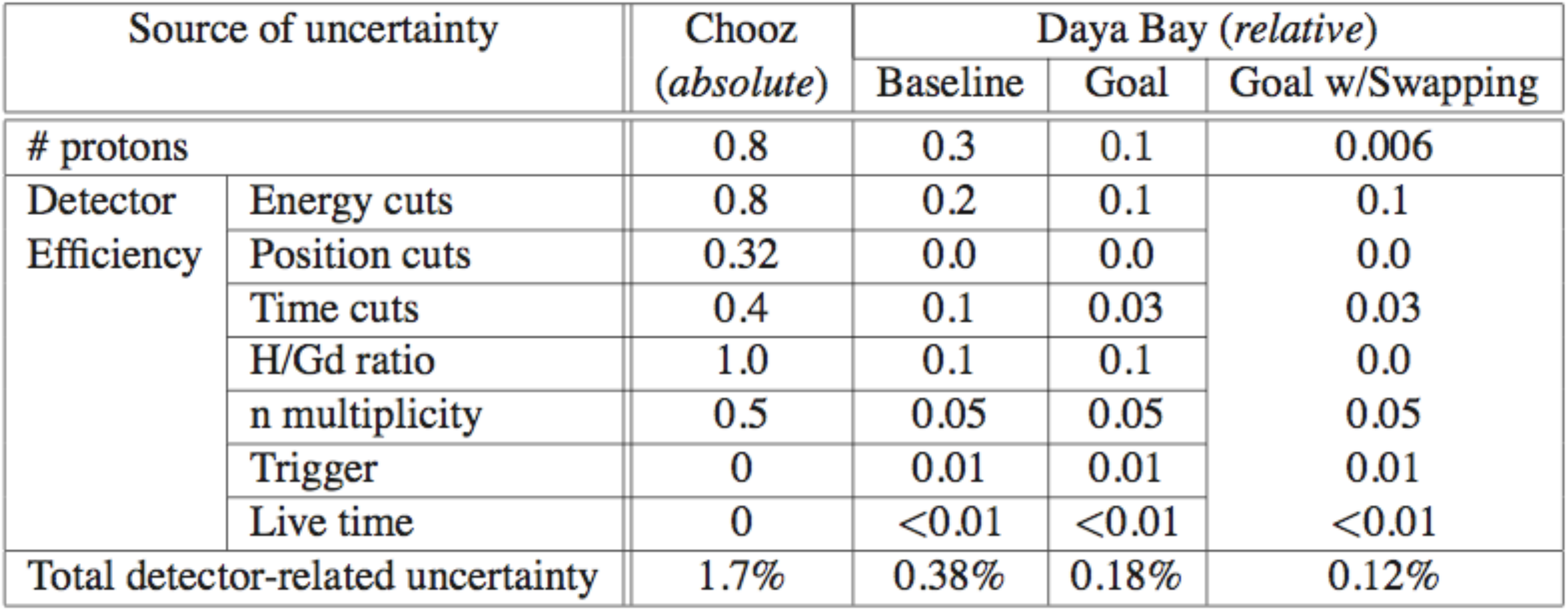


Rate (Reno)



- Besides reactor flux the rate decreases vs. time
- Scintillator degrades

Uncertainties are Small



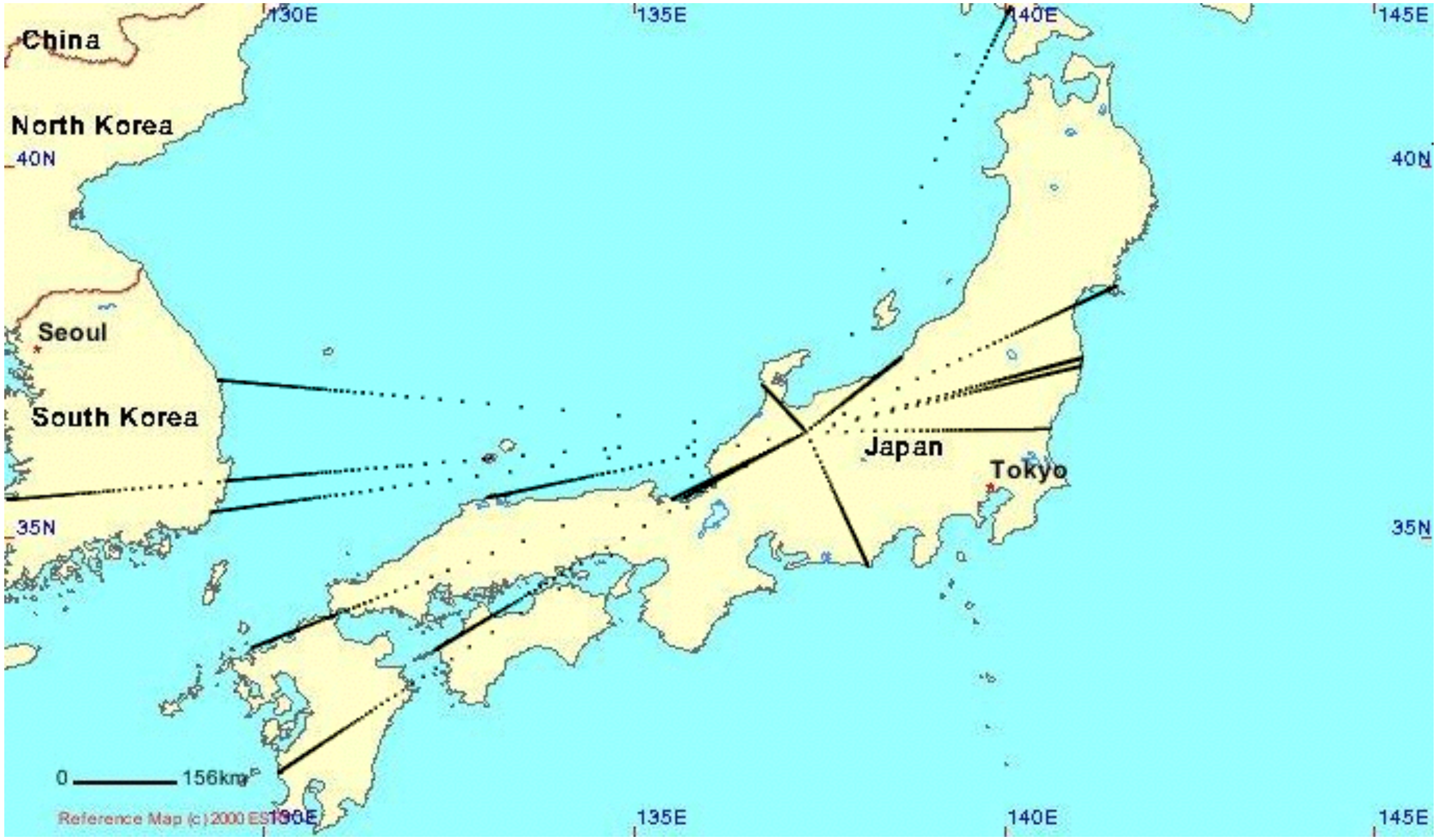
Source of uncertainty		Chooz	Daya Bay (*relative*)		
		(*absolute*)	Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	<0.01	<0.01	<0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

Why Use Liquid Scintillator?

- Solar/Reactor neutrino oscillation Δm^2_{12} and θ_{12}
  - KamLAND, Borexino
- Geo-neutrinos
  - KamLAND, Borexino
- Measure neutrino mixing angle θ_{13}
  - Reno, Chooz, Double Chooz, Daya Bay

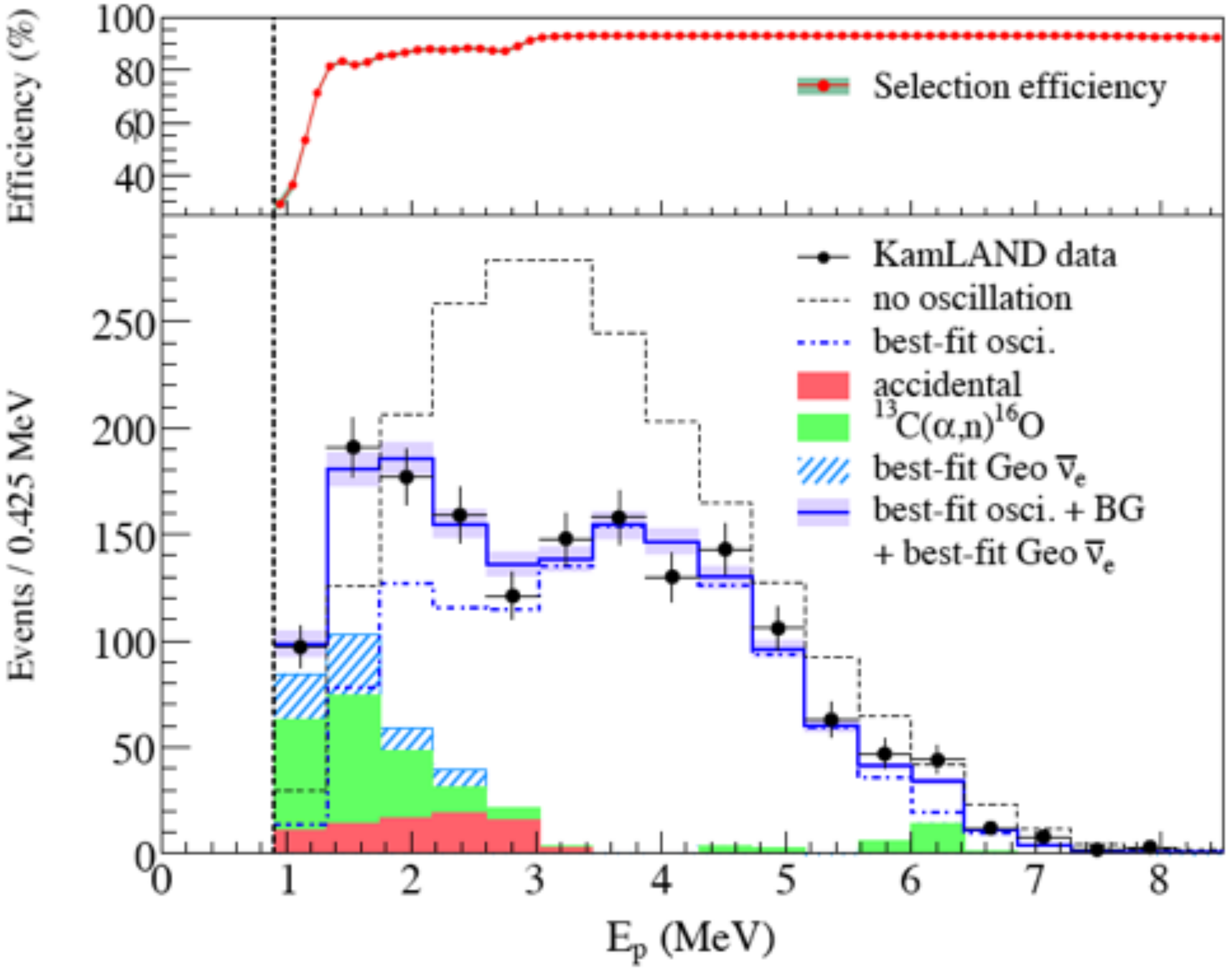
KamLAND

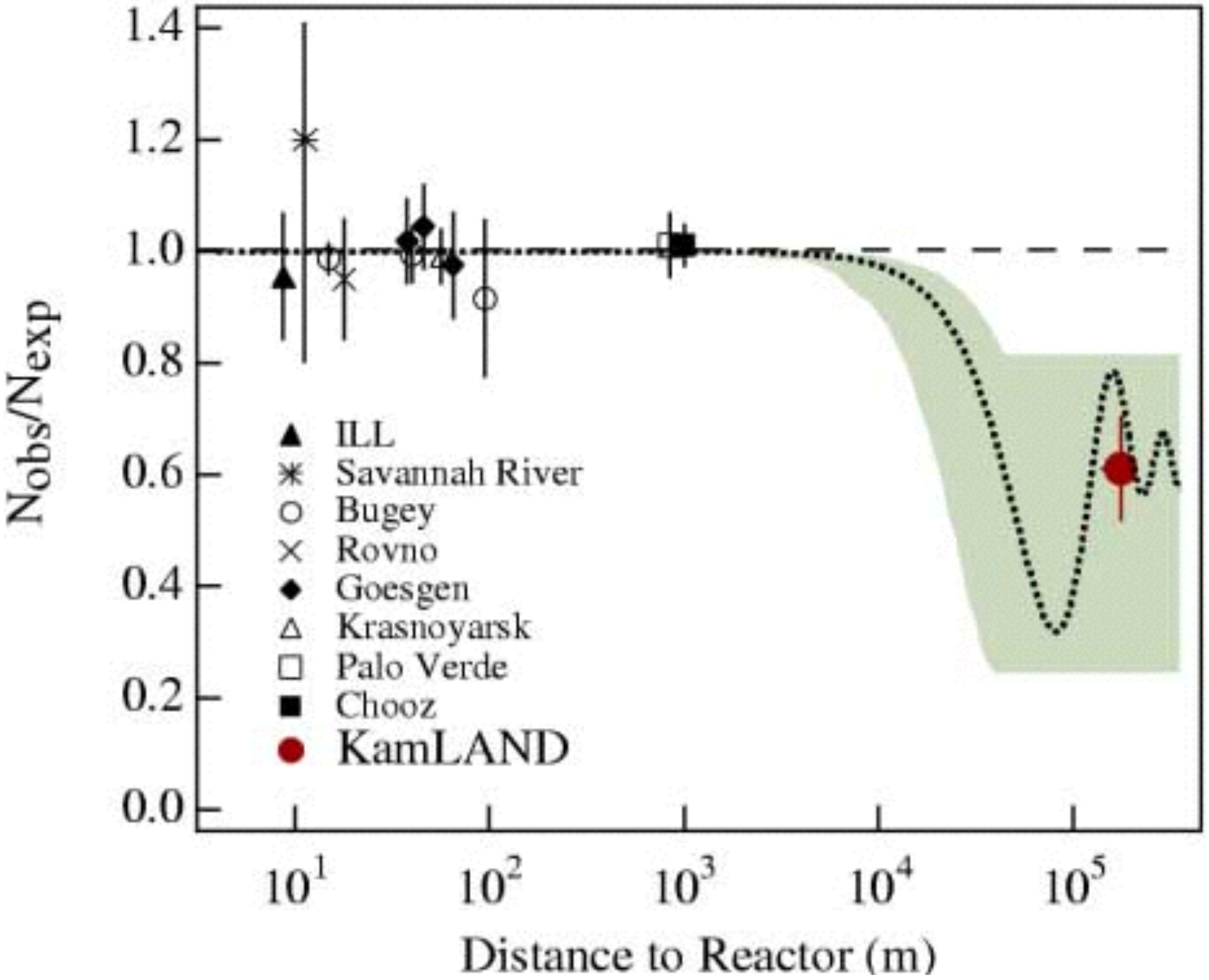
- Use the many available reactors in Japan as sources
- No directionality, so meticulous care had to be kept of power output (neutrino emission) of each reactor



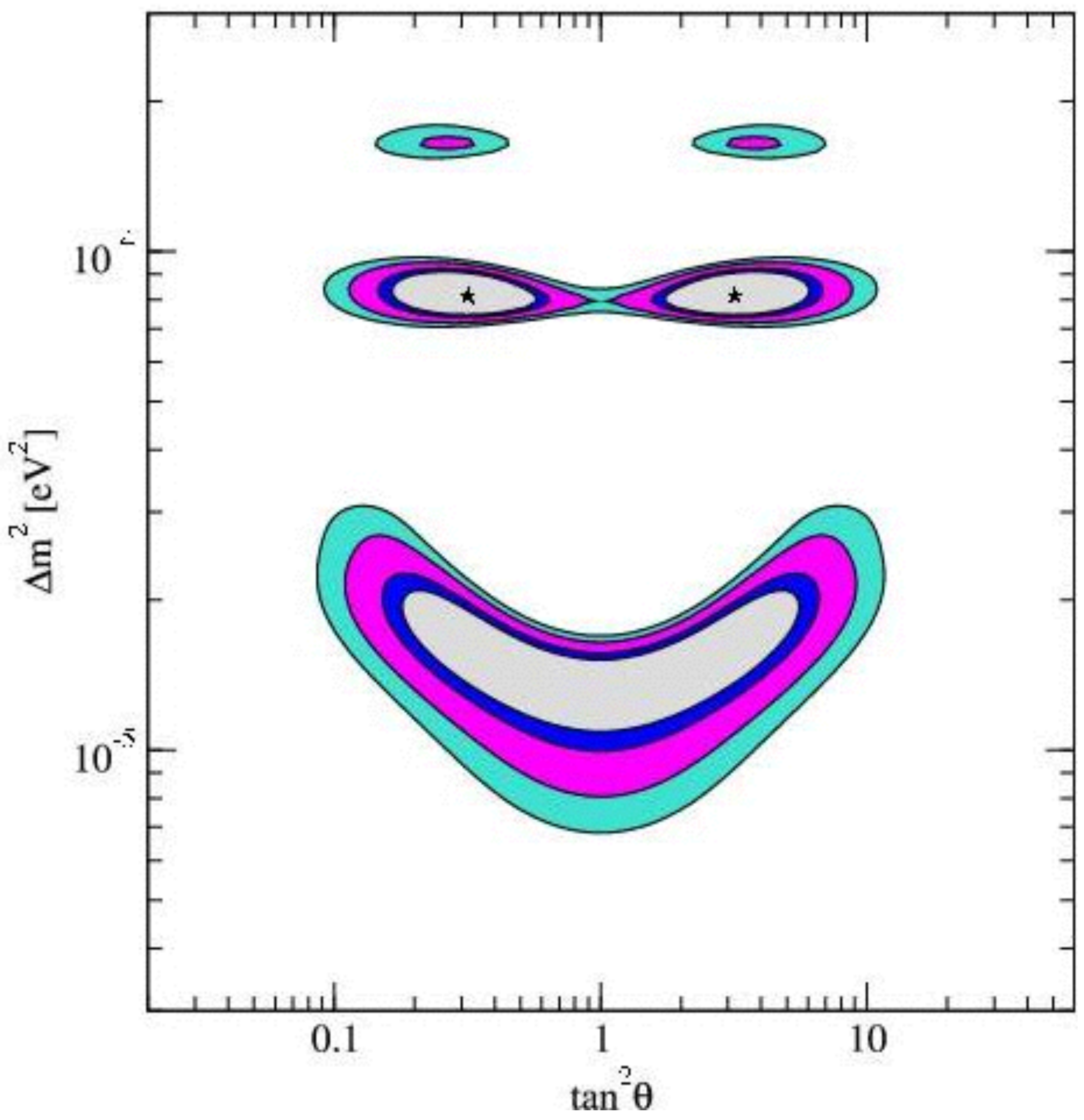
KamLAND

- Has both rate and energy spectrum measurements

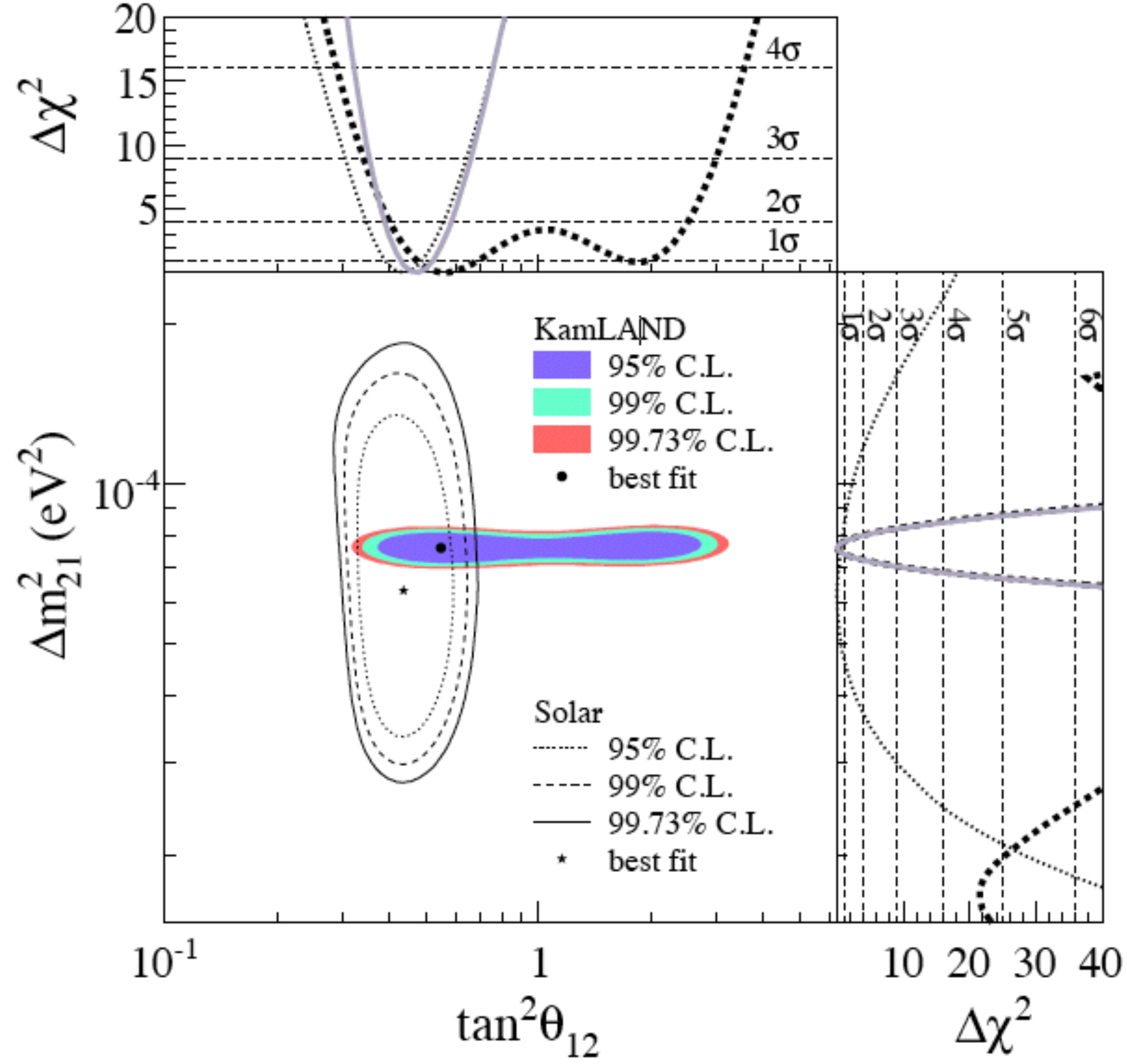




Best Result Plot?


KamLAND: *"just smiling"*

Solar/Reactor Results w/ KamLAND



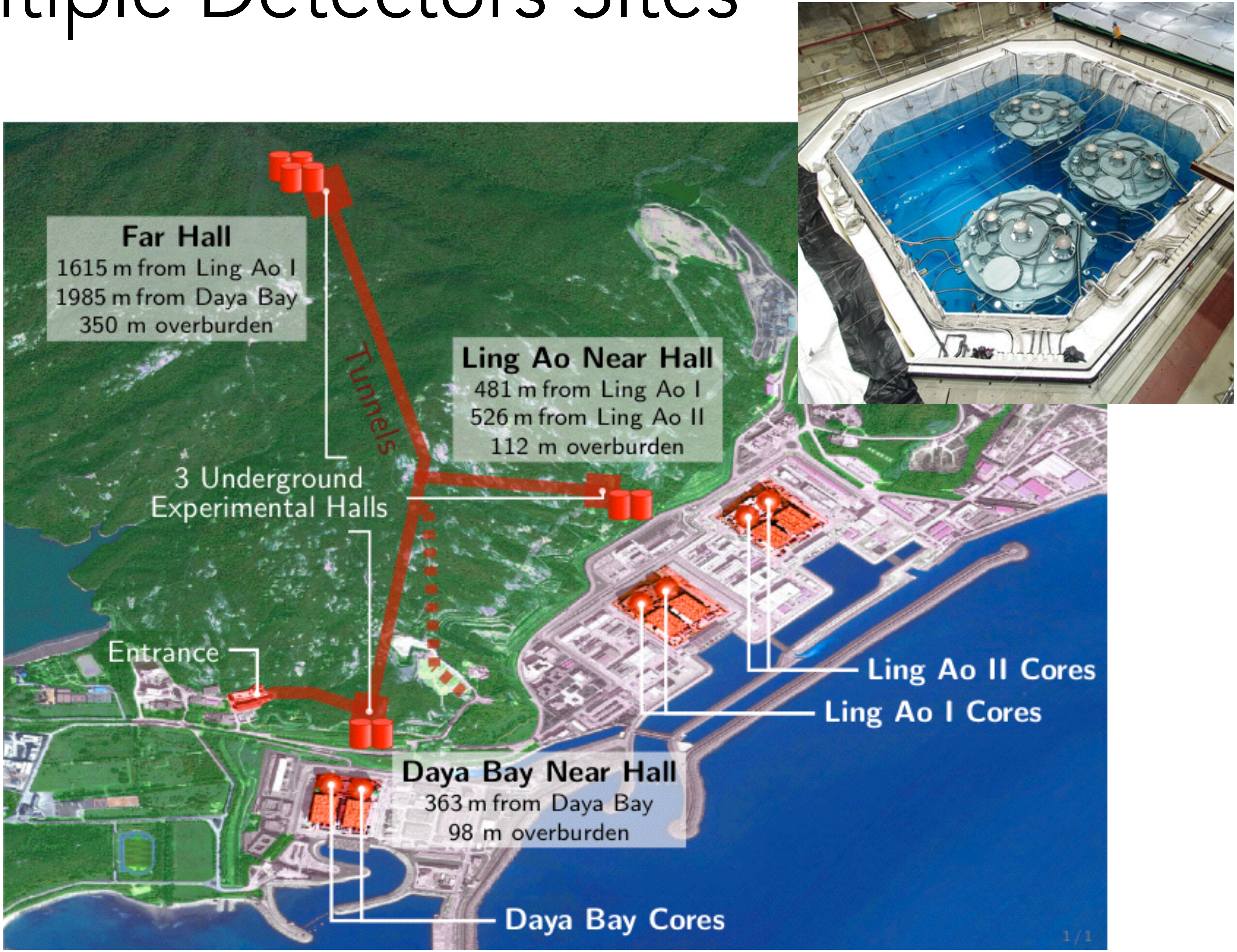
θ_{13}

- Oscillation probability of electron neutrino to electron neutrino (or anti-neutrino) is

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

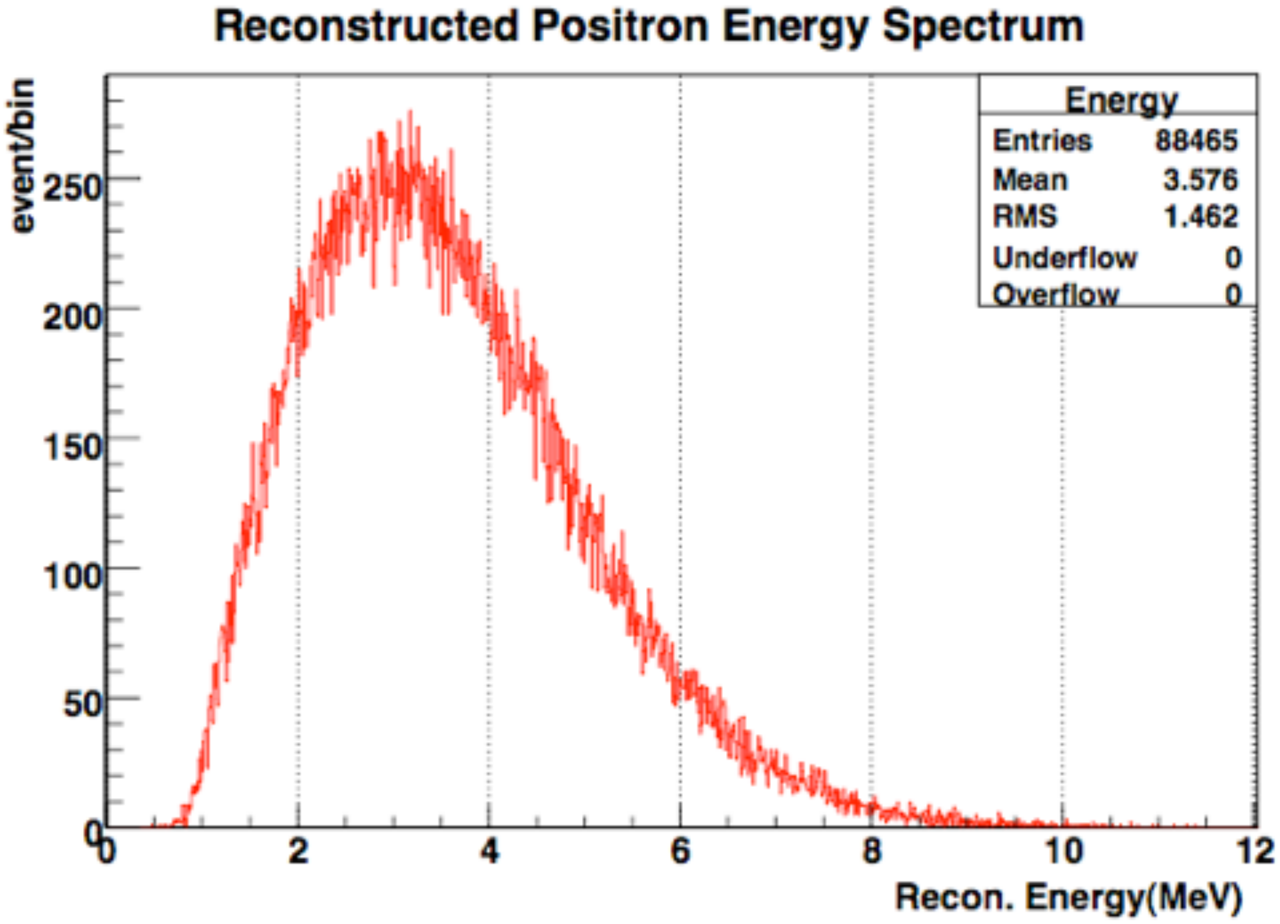
- KamLAND+Solar experiments provide the Δm^2_{12} and θ_{12} elements while atmospheric oscillation provides Δm^2_{31}
  - L is the distance between neutrino emission and detection
  - Neutrino energy is reconstructed using the scintillation light

Multiple Detectors Sites

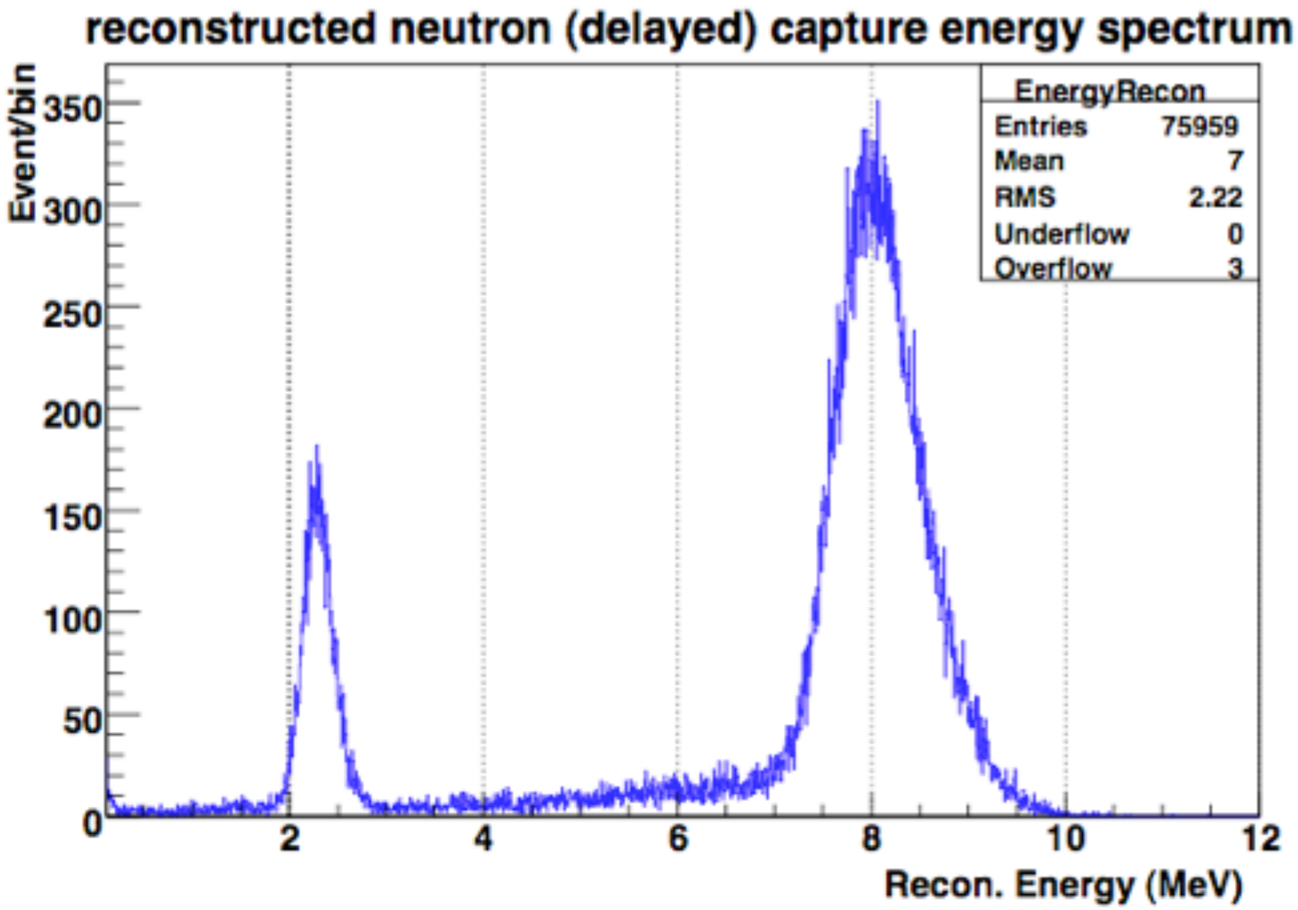


Event Selection

- Make energy cuts for prompt and delayed signal



Reconstructed Positron Energy Spectrum



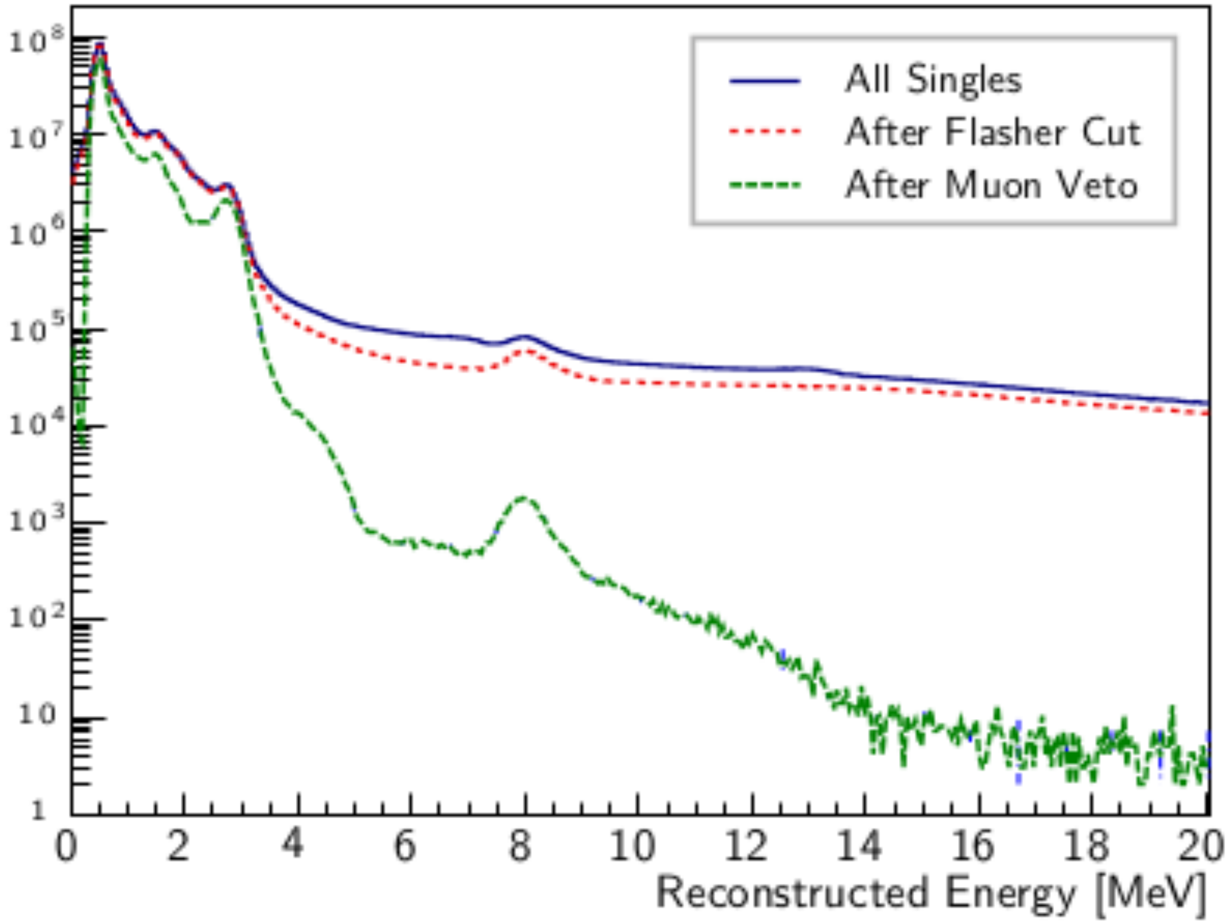
reconstructed neutron (delayed) capture energy spectrum

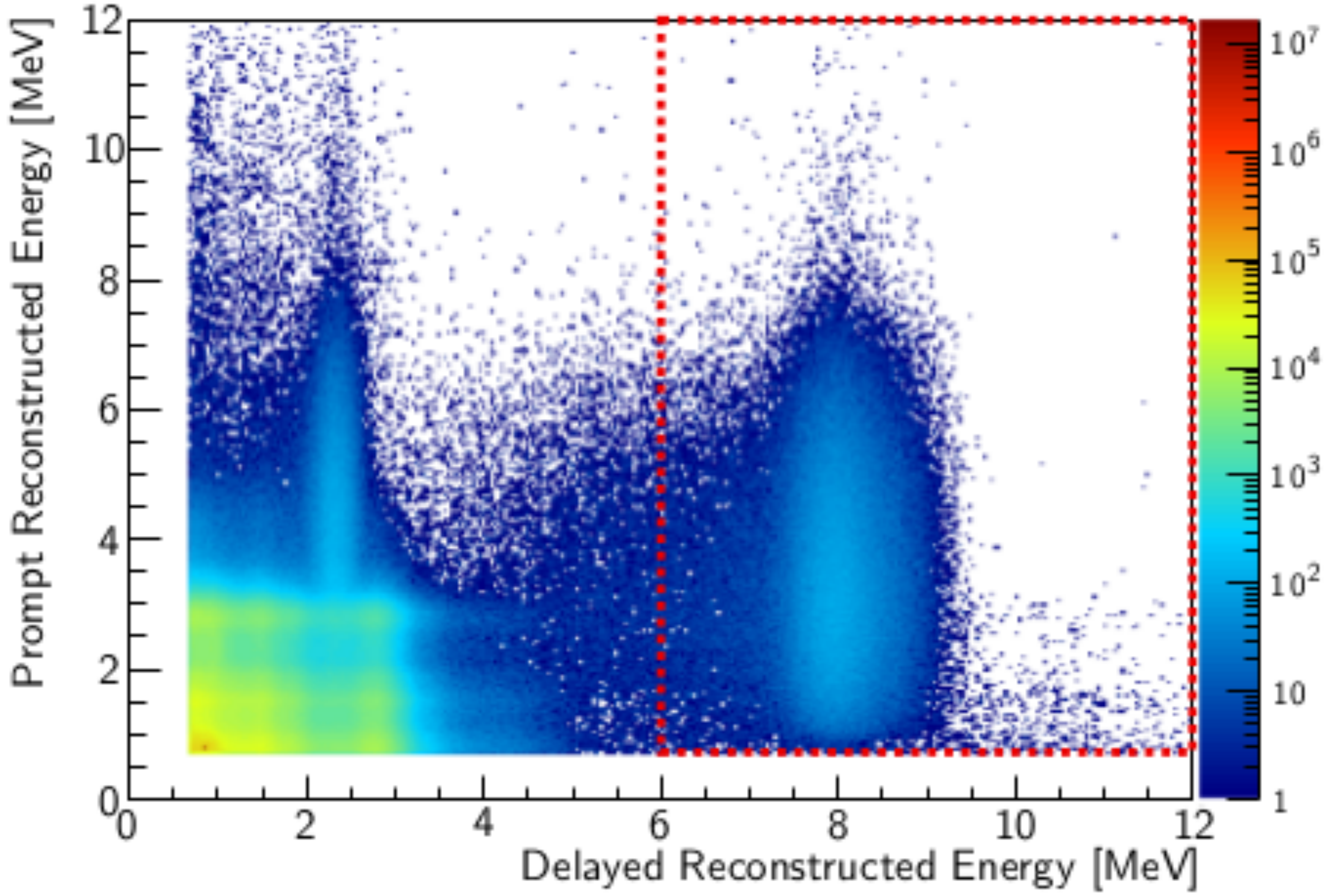
Bkg Rejection

- Energy cuts on signal (IBD)
  - Prompt energy 0.7 MeV - 12 MeV
  - Delayed Neutron 6.0-12 MeV

- Timing
  - Prompt is 'immediate'
  - Delayed 1μs-200μs

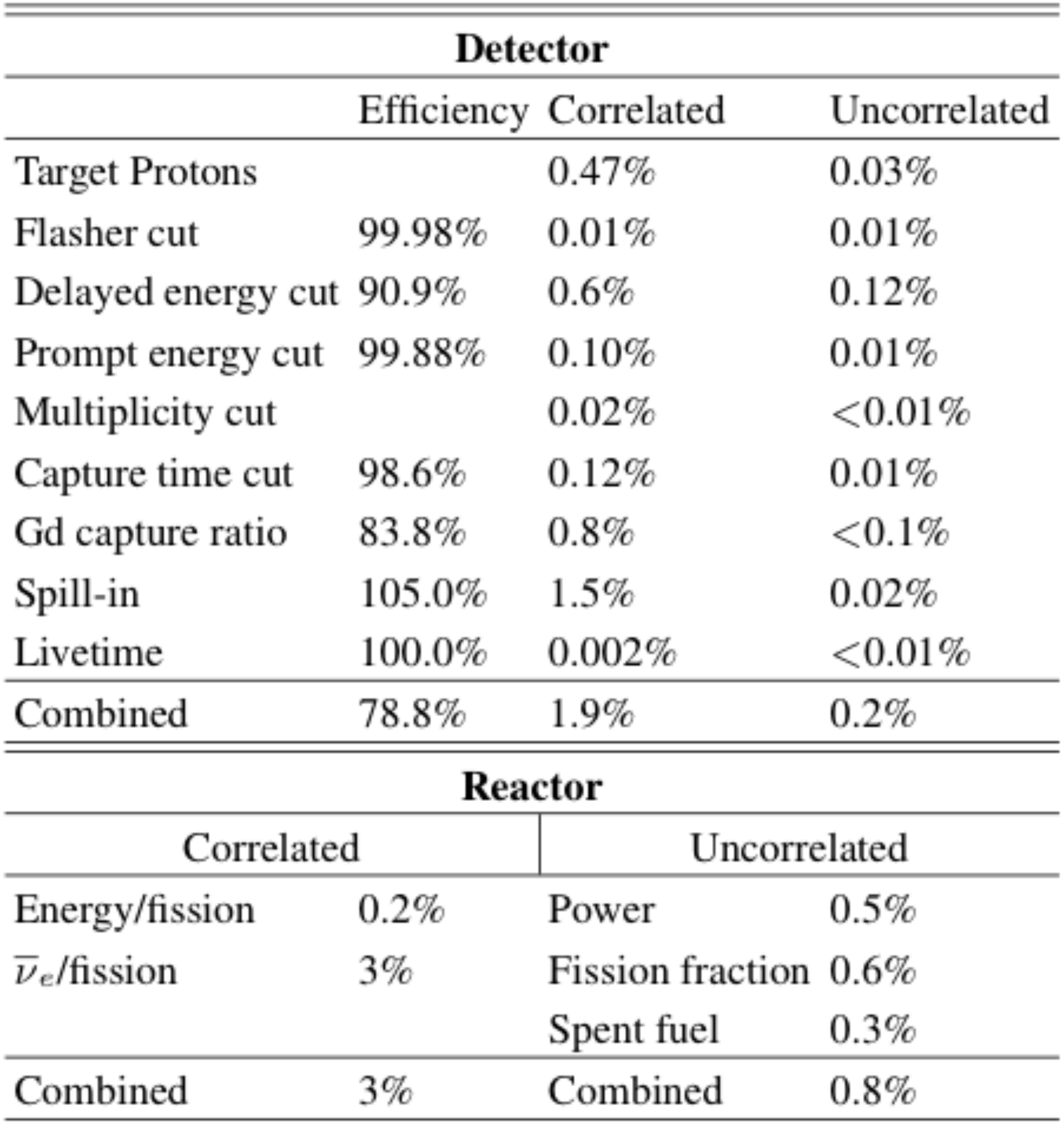
- Veto Cuts
  - Outer veto volume (>12 hit PMTs) reject -2μs to 600μs
  - Inner volume (> 3000 PE) reject -2μs to 1400μs
  - Inner volume (> 3x10^5 PE)
  - reject -2μs to 0.4s





*D. Dwyer, LBNL

Daya Bay Systematics Budget



Detector

	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

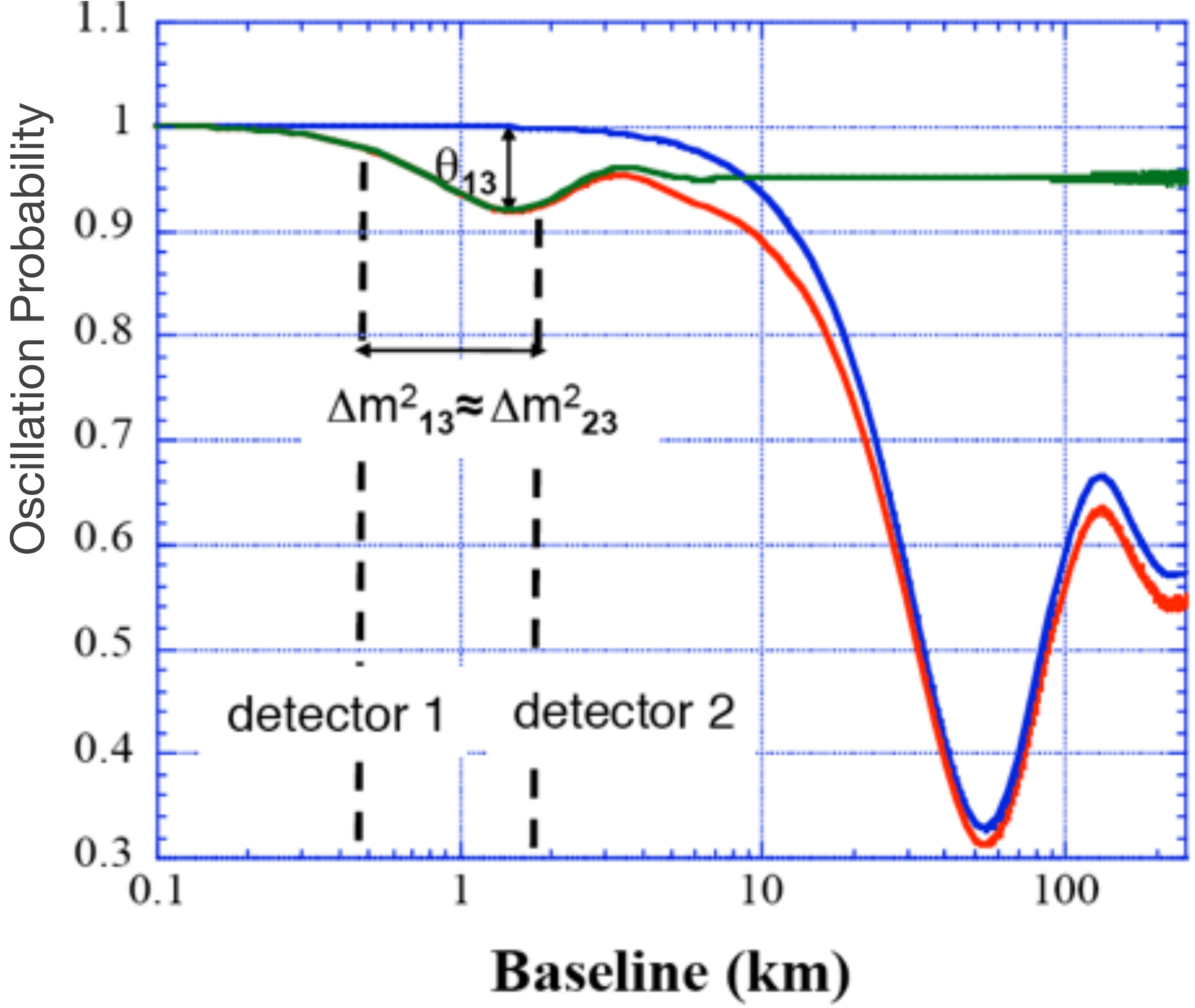
Reactor

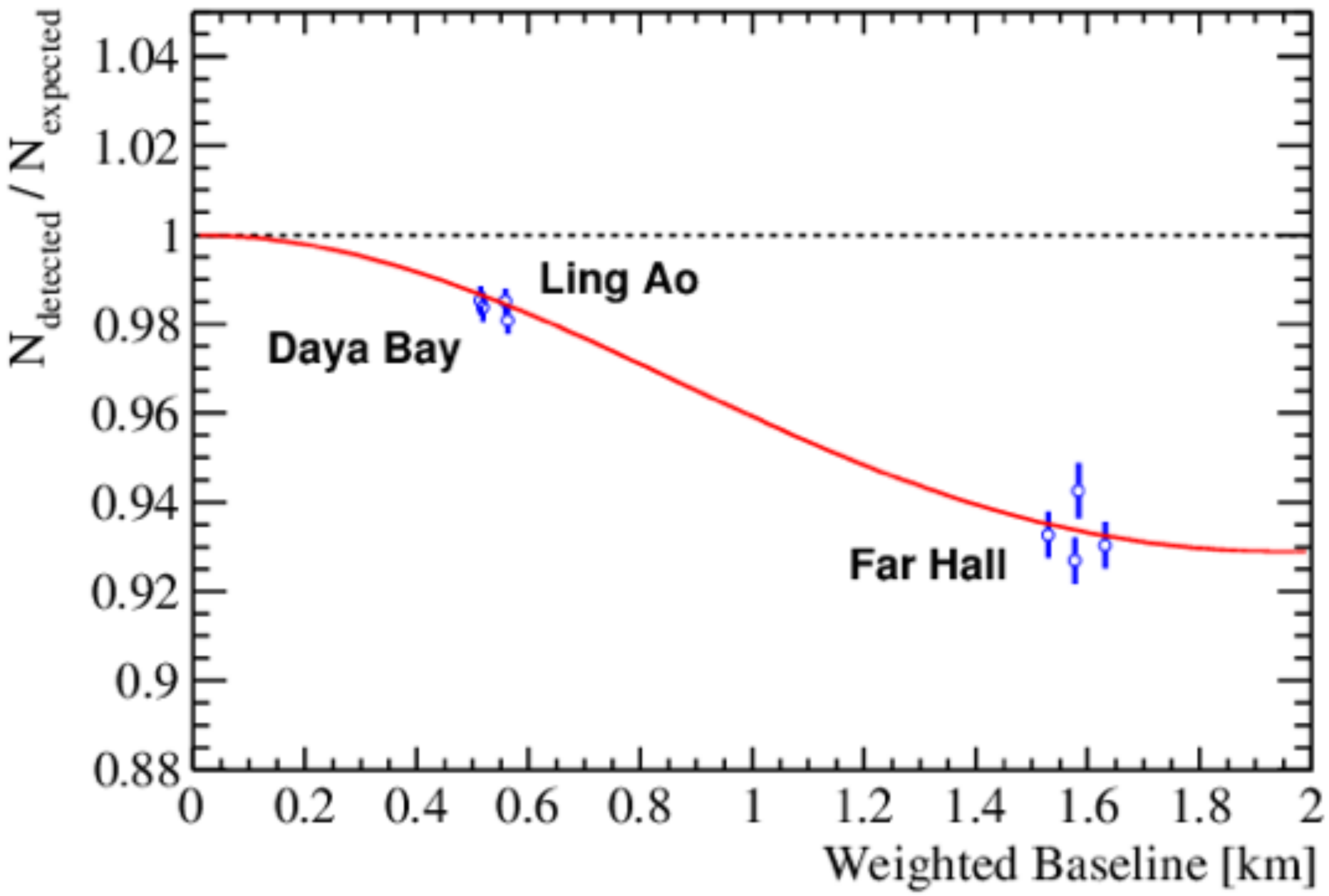
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Daya Bay Result

Small Amplitude θ_{13}

Large Amplitude θ_{12}



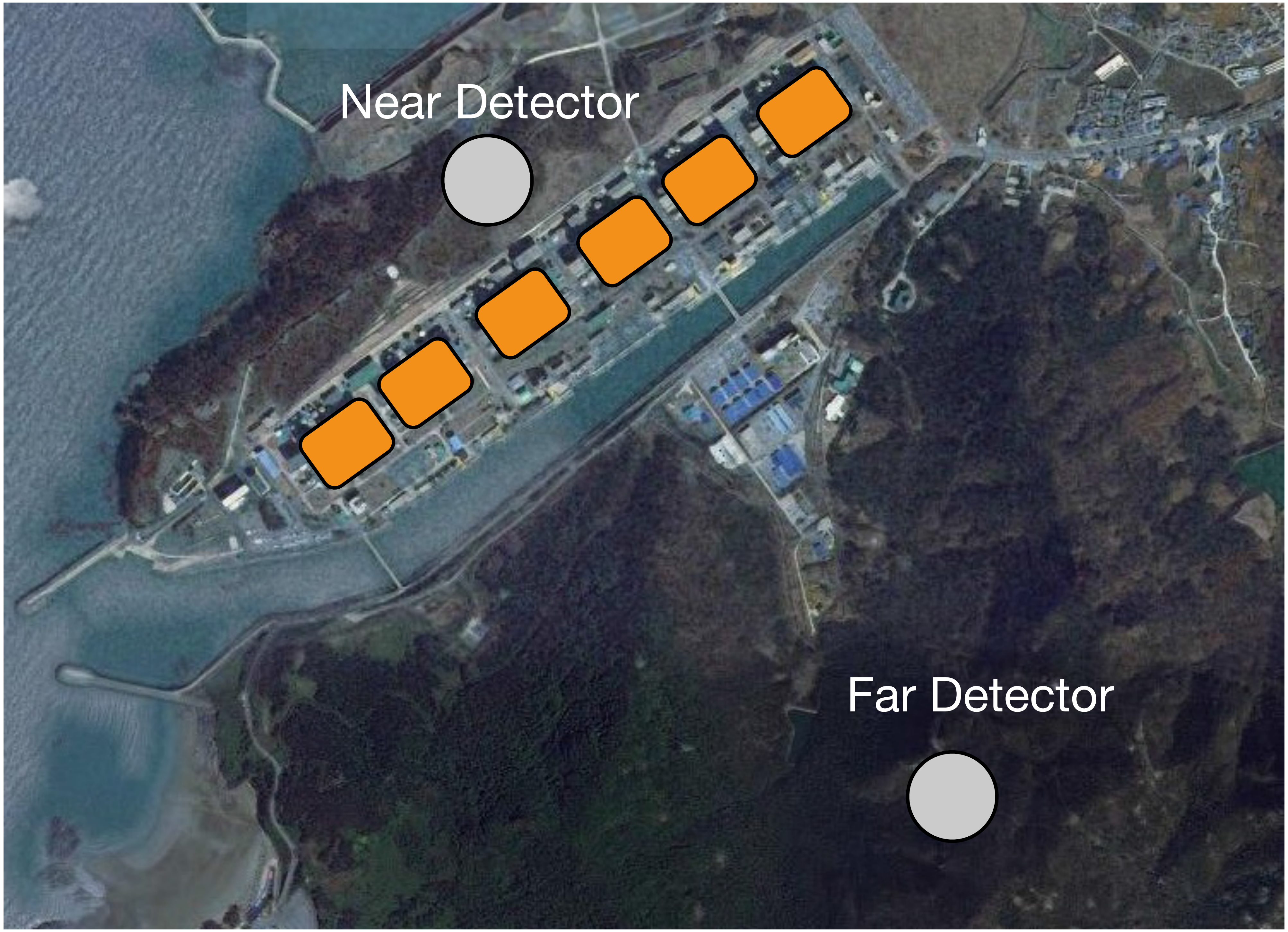


*C. Zhang, Neutrino 2014

$$sin^2(2\theta_{13}) = 0.089 \pm 0.010(stat) \pm 0.005(syst)$$

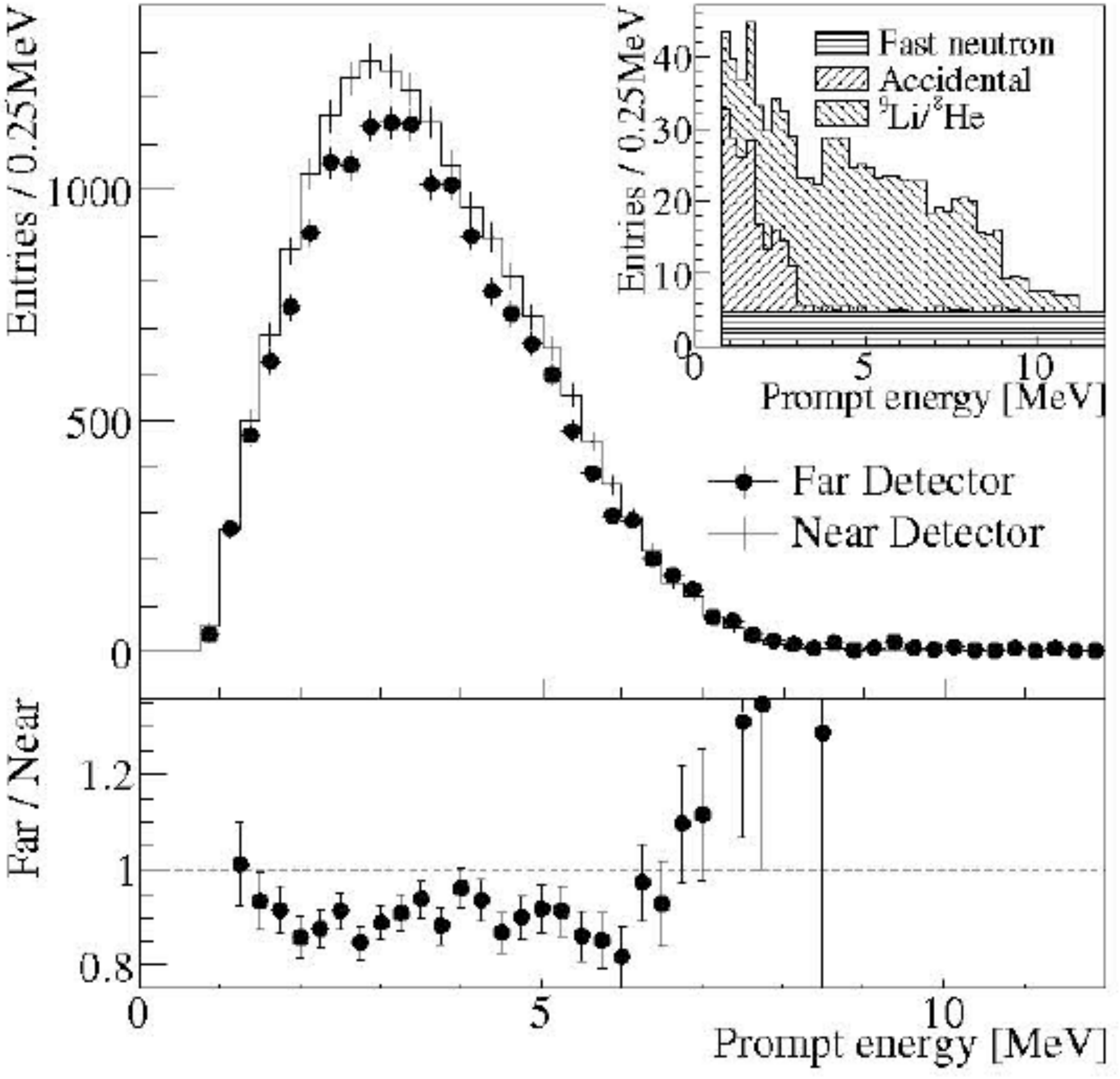
Reno Setup

- Located near 6 nuclear reactors in Yonggwang S. Korea



RENO

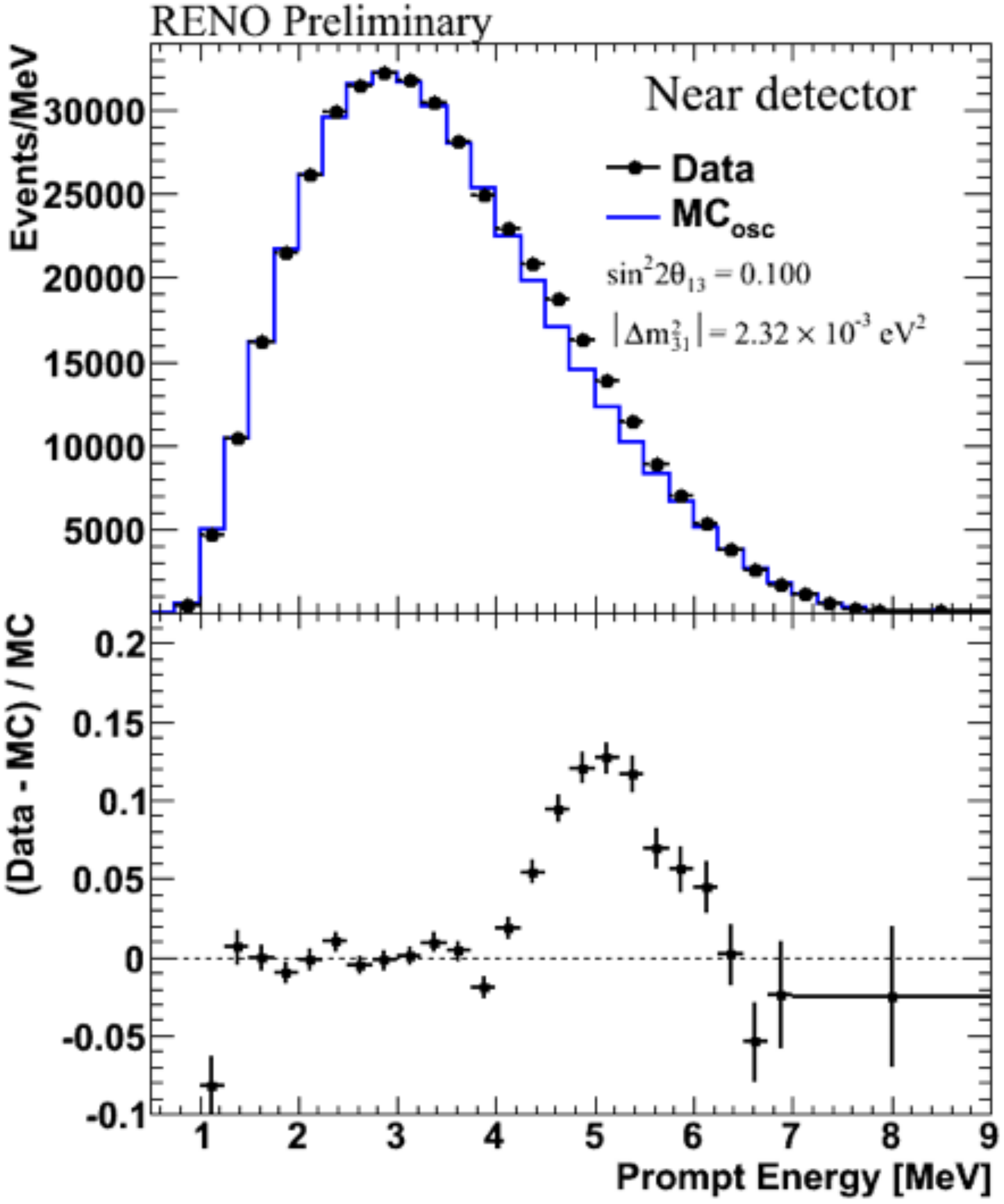
- One larger detector instead of many smaller detectors (Daya Bay)
- Consistent with Daya Bay

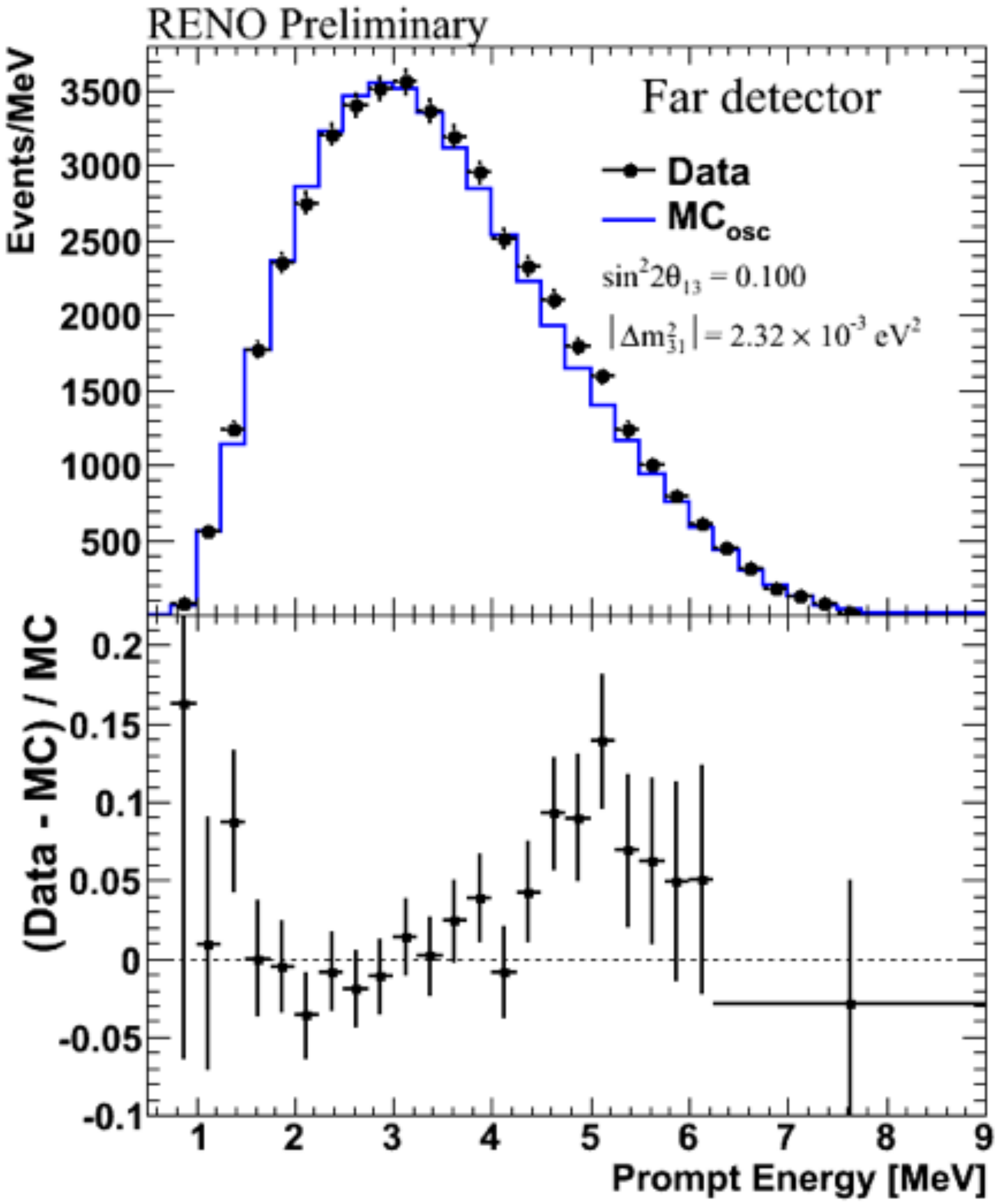


$$sin^2(2\theta_{13}) = 0.101 \pm 0.008(stat) \pm 0.010(syst)$$

*S-H. Seo, Neutrino 2014

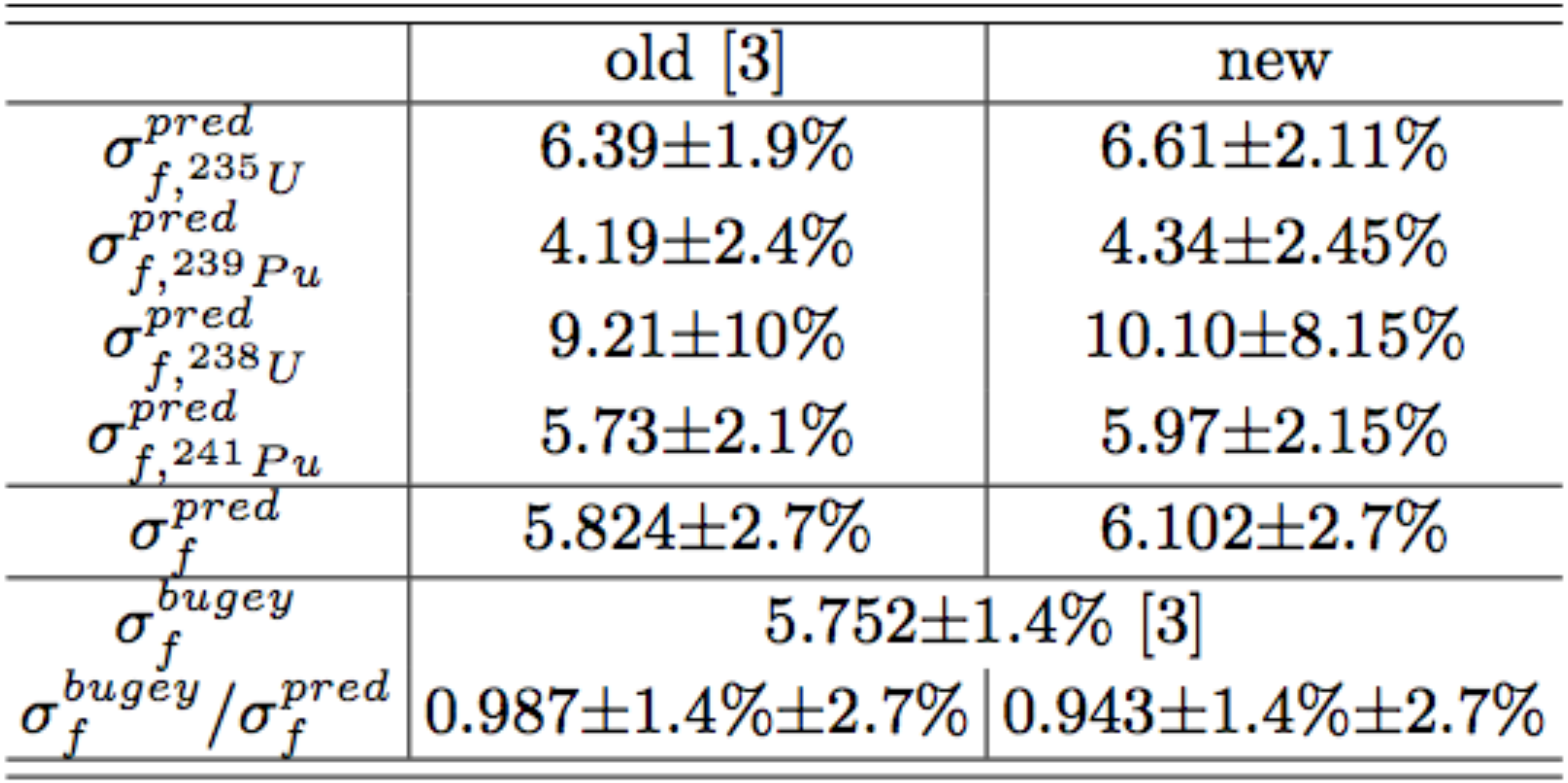
New Reno Feature





Interesting

- In 2011 reactor antineutrino spectra predictions were reevaluated with a 3% increase in flux (arXiv:1101.2663)

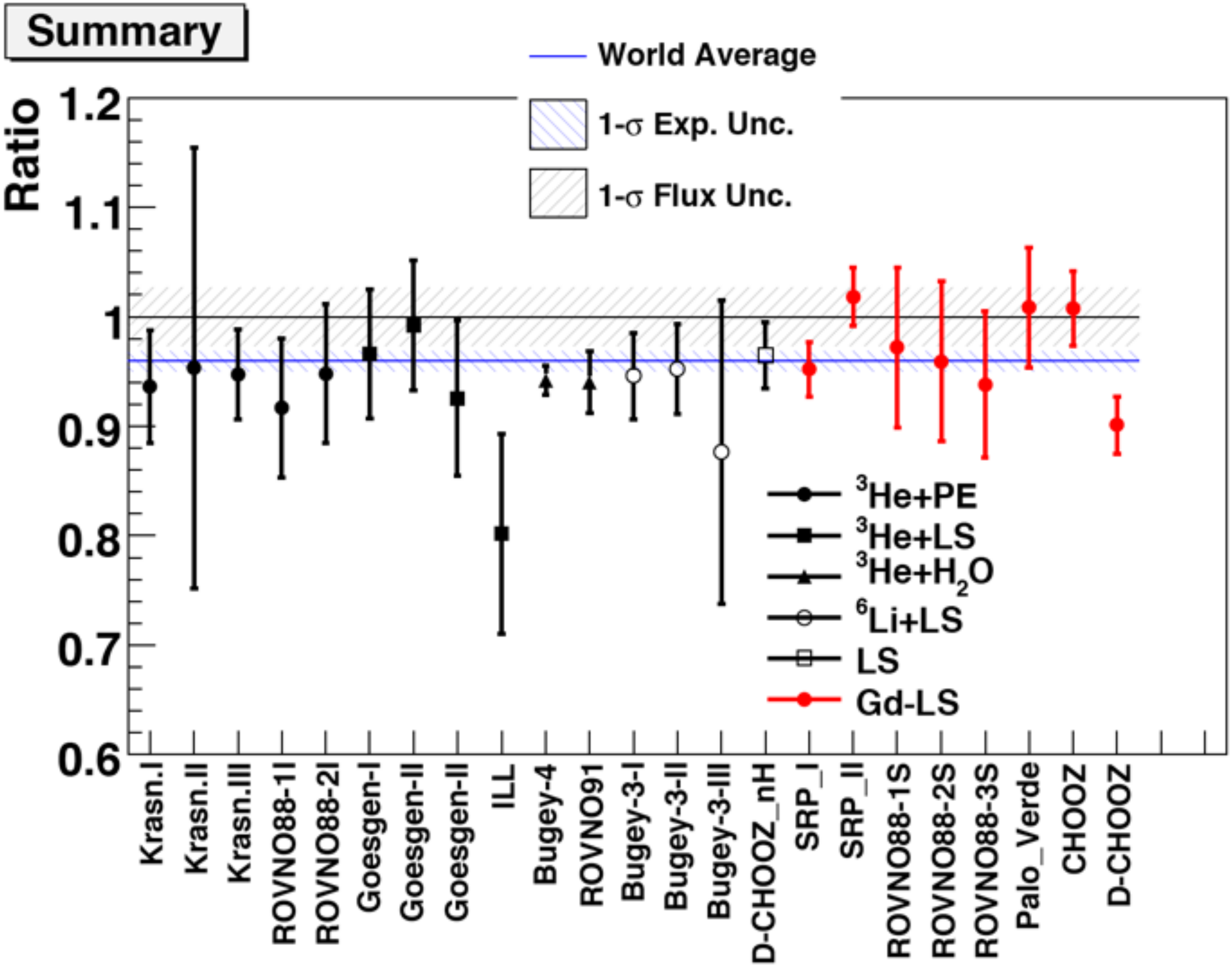


	old [3]	new
$\sigma^{pred}_{f,^{235}U}$	6.39±1.9%	6.61±2.11%
$\sigma^{pred}_{f,^{239}Pu}$	4.19±2.4%	4.34±2.45%
$\sigma^{pred}_{f,^{238}U}$	9.21±10%	10.10±8.15%
$\sigma^{pred}_{f,^{241}Pu}$	5.73±2.1%	5.97±2.15%
σ^{pred}_{f}	5.824±2.7%	6.102±2.7%
σ^{bugey}_{f}	5.752±1.4% [3]	
$\sigma^{bugey}_{f}/\sigma^{pred}_{f}$	0.987±1.4%±2.7%	0.943±1.4%±2.7%

Reactor Anomaly

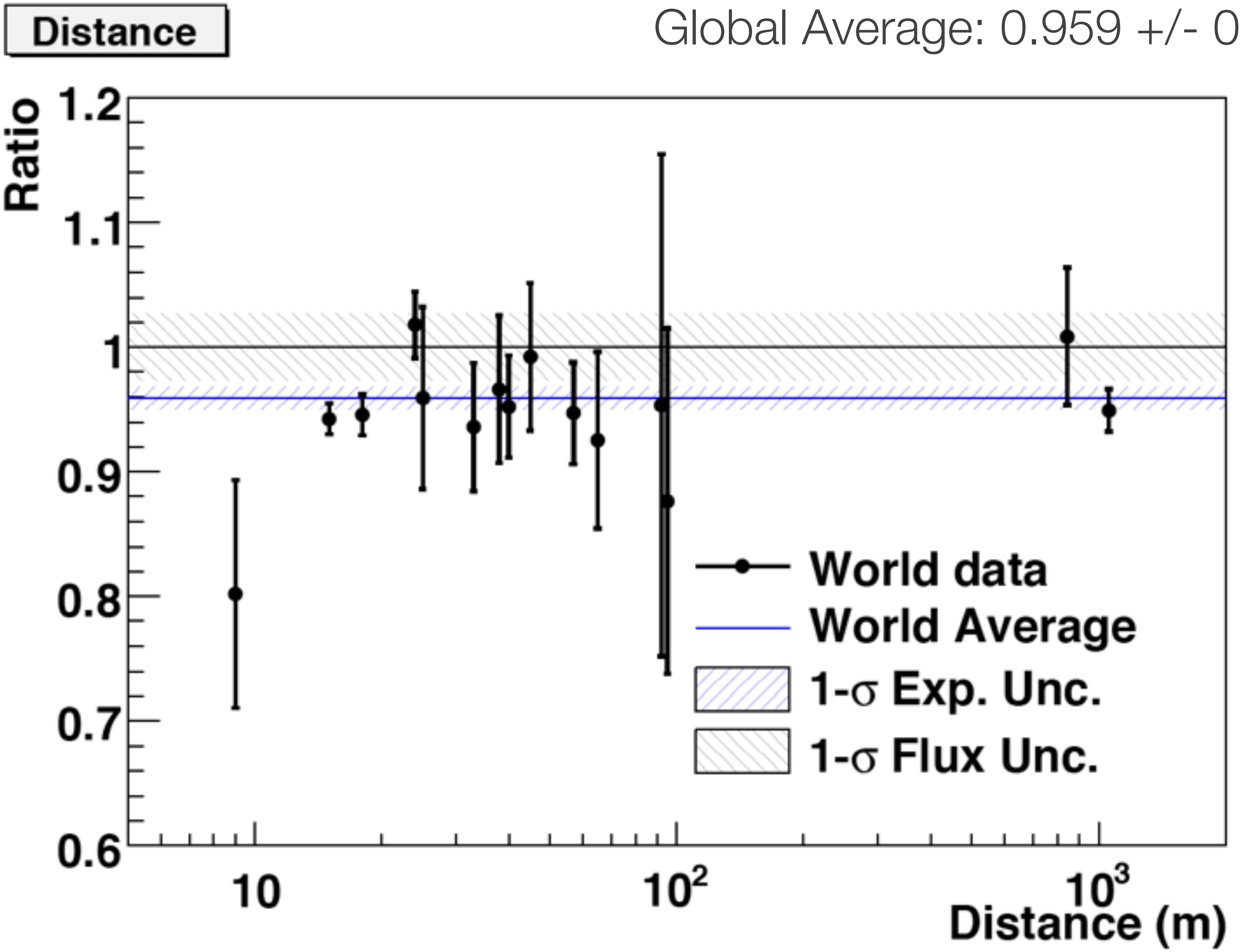
arXiv:1303.0900

Global Average: 0.959 +/- 0.009



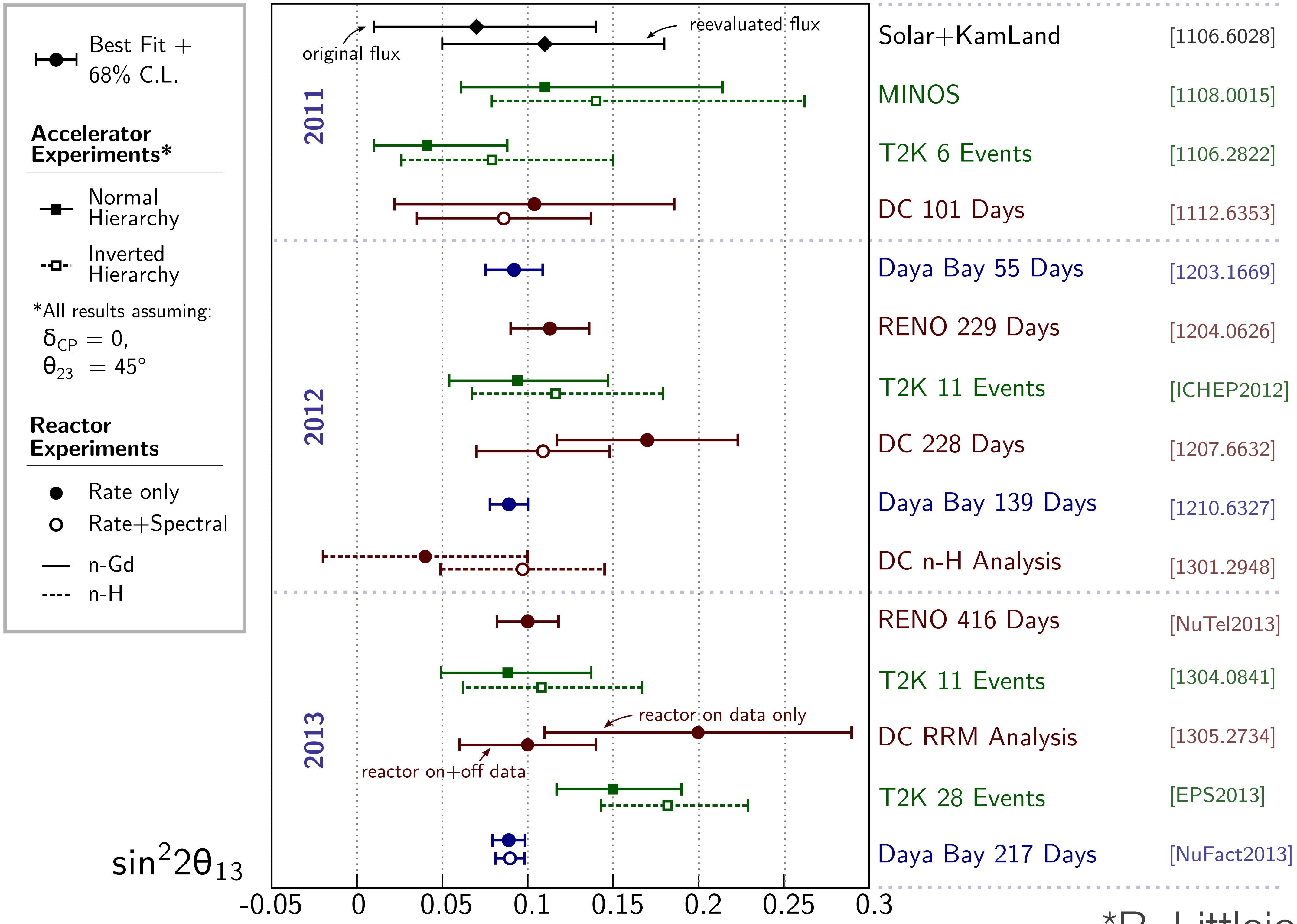
Versus Distance

Global Average: 0.959 +/- 0.009



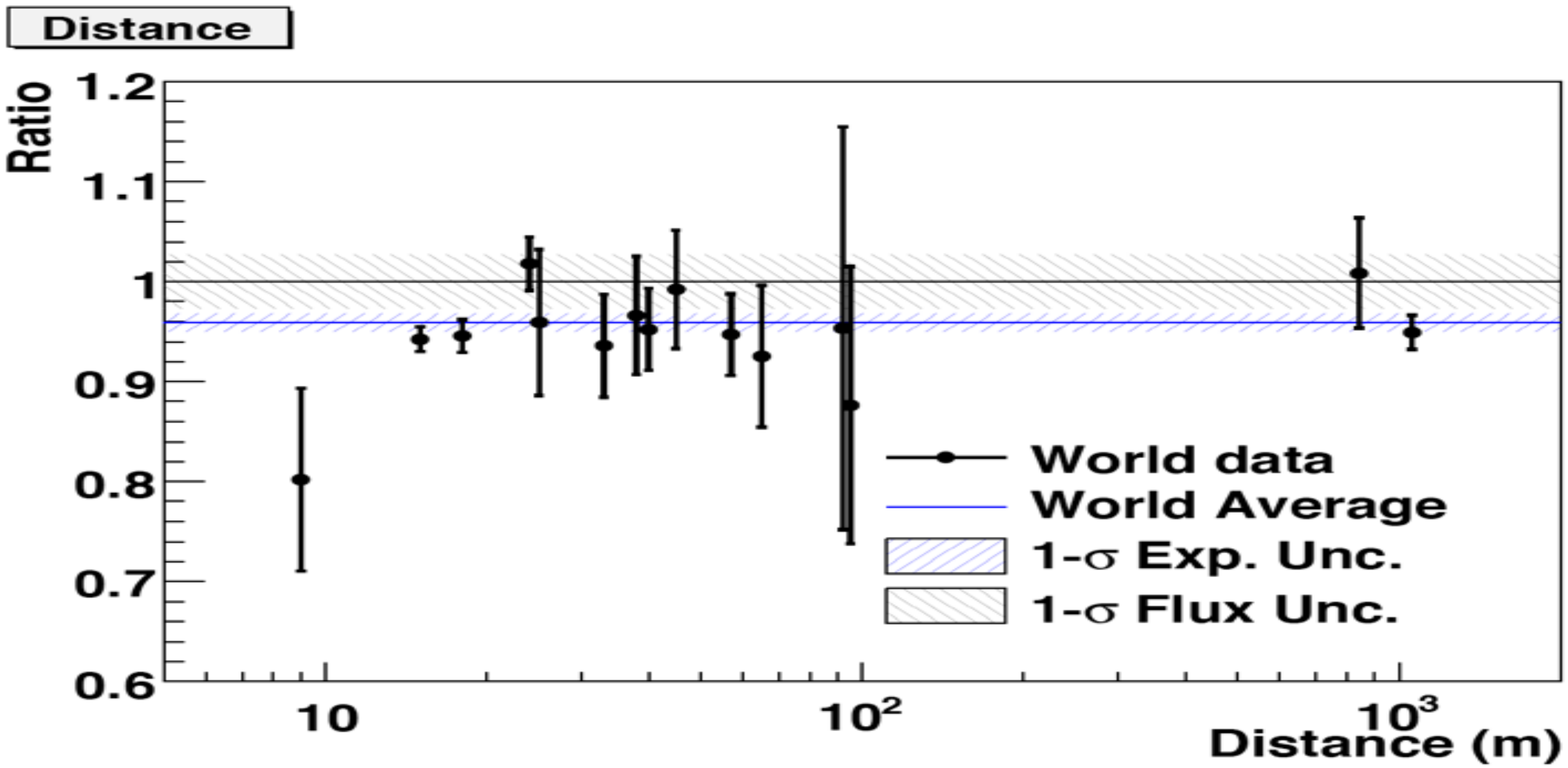
θ_{13} Landscape

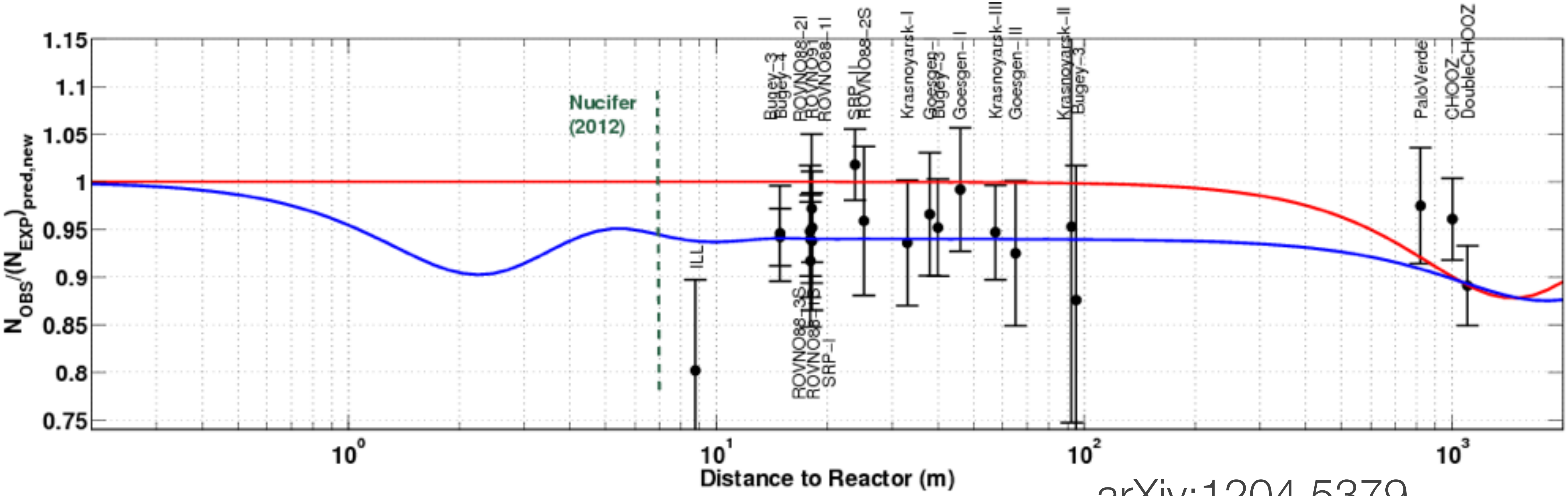
Daya Bay remains the most precise of numerous largely consistent θ_{13} measurements



*B. Littlejohn

Anomaly vs. Distance





arXiv:1204.5379

Reactors Wrap-Up

- Inverse Beta-Decay is most common detection channel
- Low radioactivity in construction is essential
- Excellent measurement of solar oscillation parameters and θ_{13}
- Rate anomaly seen